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NAVAL SURFACE WARFARE CENTER
Dahlgren, Virginia 22448-5100

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TOTAL SHIP SYSTEM ENGINEERING VISION AND FOUNDATIONS

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BERNARD G. DUREN
JAMES R. POLLARD

COMBAT SYSTEMS DEPARTMENT

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Bernard G. Duren, James R. Pollard

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Commander
Naval Surface Warfare Center, Dahlgren Division (Code N04)
17320 Dahlgren Road
Dahlgren, VA 22448-5100

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This report considers an effort to reinvent the process by which the Navy transforms operational requirements into surface combatants. The objective is to articulate a new framework for total ship system engineering. For this, three things are necessary: a culture of teamwork permitting a unified system engineering effort; a common framework for total ship system engineering; and agreed-to concepts, standards, and tools for design integration. The work is being conducted as a collaborative effort involving three warfare centers and various headquarters activities in Washington. The strategy involves a focus on a family of backbone control structures that provide the means for mission teams to operate a ship as a coherent entity. Subsequent efforts will address how the approach can be implemented in future programs.

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FOREWORD

This report attempts to lay foundations for a total ship system engineering process. It results from a continuing effort to construct elements of a vision and strategy for improving the total life cycle effectiveness of surface combatants in the 21st century. The aim is to articulate a disciplined, top-down approach that stimulates consideration of new technologies and new ways of doing business.

The effort benefits greatly from the guidance provided by a group of key Navy acquisition executives, working together as a team to prepare the way for a new generation of world class surface combatants. Contributing activities have included AEGIS, Cruise Missiles and Unmanned Aerial Vehicles, Theater Air Defense, Undersea Warfare, PD-60 and PD-70 of the Space and Naval Warfare Systems Command, and the Engineering Directorate of the Naval Sea Systems Command. The flag-level members were supported by an administrative team drawing from their staffs as well as the Naval Surface Warfare Center (NSWC) and the Naval Command, Control and Ocean Surveillance Center. Known to each other as the "Gang of Six," this group has provided strong support to the idea of building a culture of teamwork that overcomes the stovepiping of the past.

Several related efforts must be acknowledged. Substantial help was obtained from the Surface Combatant 21st Century (SC-21) War Room at NSWC Dahlgren Division, led by John Burrows and sponsored by Rear Admiral George Huchting, USN. The Naval Air Warfare Center's Training Systems Division and the Naval Postgraduate School at Monterey have also contributed. Another is a strategic thrust by NSWC to provide a capability for the Navy to engineer ships as systems. The Carderock Division is hosting this effort, in which all divisions of NSWC are involved.

Approved by:

Leaton M. Williams, III

LEATON M. WILLIAMS III, Head
Combat Systems Department

CONTENTS

ILLUSTRATIONS

EXECUTIVE SUMMARY

A number of serious difficulties must be overcome to meet the emerging challenges of the 21st century. First, we face an era of austerity and change as US forces are downsized. Second, we also face considerable uncertainty due to the diversity of threats and environments which could arise in future conflicts. Third, it must be recognized that revolutionary changes are taking place in warfighting systems and methods. Given the complexity of warfare tasks, superior system engineering will be needed to create new combatants, tailored to the joint and expeditionary warfighting concepts now beginning to emerge. For all these reasons it is necessary to prepare the way for a new generation of world class naval combatants.

This report is based on the premise that future Navy ships should be engineered from a total ship perspective to serve as elements of a capable and jointly interoperable Navy warfighting system. **Chapter 1** reviews the basic concept of total ship engineering; that is, a warship must act as a coherent warfighting system, all parts working in unison to maximize operational effectiveness. From the hull form to the launchers and missiles, every part of the ship must contribute to the overall goal of ordnance on target.

Chapter 2 gives the basics of a system engineering approach to total ship engineering. System engineering is a robust approach to design, creation, and operation of complex systems. Applied to surface combatants, a suitable system engineering process will integrate ship design, construction, and support activities over the entire value stream. The idea is that future ships must weave combat, support, hull, and machinery modules into a "system of systems" configuration with a mix of firepower, stealth, survivability, and affordability characteristics that meets all operational requirements. This demands efforts to establish a comprehensive system engineering framework for ships.

Chapter 3 considers elements of a control architecture for surface combatants. It constructs a process reference model for the surface ship domain, indicating that control structure drives the ship's ability to act as a coherent entity. The process reference model captures basic missions and operating concepts, defines key technical concepts, and provides a vocabulary that will permit sharing of ideas throughout the Navy community. Building blocks for such models include elementary sense, control, act operations and three types of interconnecting paths. Action paths sequence basic operations to perform mission tasks. Information paths represent data flows, while command paths represent lines of authority and responsibility. These are the basic intellectual tools necessary to arrive at a clear understanding of what surface combatants are, what they must do, and how they should be built.

Chapter 4 considers what the control structure of a surface ship should be, from a top-down perspective. The strategy for partitioning control resources on a total ship basis is rooted in basic principles of system engineering. The first principle to be considered is that the aim of design must be to help the warfighters in achieving their operational objectives. The mission teams carried to an operating area, where they may be called upon to maintain presence or to deliver high-tech firepower against an adversary, must be the primary concern.

At this point the overall control problem is broken down into a relatively small number of backbone areas (or core subsystems). Three backbones are considered necessary: one to control mission operations, a second for plant control and readiness, and a third for management of information flows. The mission operations and plant control areas reflect the traditional partitioning of combat from hull, mechanical, and electrical systems. However, both are seen as total ship constructs and it is recognized that in future ships the position of the boundary may change. Maneuver and damage control coordination are seen as increasingly important concerns that may move across the boundary. The third backbone area, information management, recognizes that information is a resource that must be coordinated on a shipwide basis and that special attention may be needed to create the necessary means for coordination.

The approach to partitioning represents a critical step in total ship system engineering. A decision must be made very early in the process, and it is all too easy to find convenient pieces without establishing clearly how they will work together to form a well-integrated operating entity. The structure identified at this point serves as a framework for defining and controlling the process of top-down system engineering.

Chapter 5 considers a development process matched to the desired control architecture and reflecting an enterprise strategy for total ship system engineering. The chief concern in process definition is to ensure all major design decisions are based on what's best in terms of overall warfighting capability, rather than what's best for any particular component or class of systems. This makes total ship system engineering as much a process control or coordination problem as it is a technical problem. Overall, four main points are developed.

- **The development organization must be tailored to the desired architecture and engineering process.**

The main features of the development organization are based on the system engineering principle that work units should be organized around the loosely coupled subsystems formed by partitioning. The implication is that a partitioning for total ship design must be driven first and foremost by operational considerations, and the development team structured accordingly, rather than the other way around. The first concern must be to ensure that a basic understanding of mission teams and tasks is established. The development team must then address overall ship design, the definition of backbone control structures, and the definition of specific operating processes, adequate to meet all mission needs. These represent the principal components of the projected development team. Each component will make a key contribution to creation of a total ship "system of systems" from the host of individual systems delivered to the shipyard. Because it must deal with acquisition and integration of individual systems as well as overall ship construction, team structure is a bit more complicated than the operational control structure.

Designers and builders of future naval combatants must escape from stovepipe thinking and learn to rely on global or team thinking. The development organization should be structured to maximize value delivered to mission teams on a life cycle basis. The team leader activity is expected to control the overall design process, including weight, space, and cost budgets; the strategy for integration and control of mission capabilities; and creation of the mission critical systems that are the reason for taking the ship to sea. The supply chain should be structured to take advantage of the best practices devised by firms around the world. Open specifications would be used and information relating to process improvement (best practices) would be shared. Transactions among team members should be observed to identify opportunities for gains in productivity.

- **A unifying sense of purpose and direction must be created to knit the people involved into an effective team.**

The first and most important step is probably to form a cadre that is able to consider tradeoffs from a total ship perspective. This calls for a broader perspective than usual, but one with a full appreciation for, and easy access to, the specialized technical knowledge of functional activities and the warfighting community. In particular, some way must be found to foster and control dialog between the different engineering disciplines involved.

It is difficult to create a foundation for total ship system engineering that spans all the disciplines (technical and operational) involved. The trouble is that each discipline has its own conceptual framework, tailored to the goals, values, and character of its work and fundamental to effective teamwork. This framework is passed to each generation of recruits and colors perception of new ideas, sometimes making them seem irrelevant or contrary to accepted methods or bodies of knowledge. Fortunately, this is an obstacle that can also be a solution; that is, an appropriate conceptual framework can be established to support total ship system engineering. In essence, this report is aimed at producing such a framework, with associated design concepts, standards, and tools.

- **Backbones are the key to building warships as systems.**

A key aspect of modern technology is the potential for gains in capability and affordability through sharing of resources across subsystem and element boundaries. A wide variety of resources (sensors, computers, and displays; magazines and launchers) can be shared in this way. For this reason the key problems of design are moving upward in the hierarchy of systems, and formal trade studies become necessary for novel partitionings of embedded combat and ship systems.

- **Warfighters must be involved in the development process.**

Flexibility is a major consideration in building forces to cope with an uncertain future. The hope is that flexibility will enable US forces to respond quickly to emerging threats, extend US reach to any part of the globe, and adopt new technologies with ease. Having acknowledged the importance of flexibility, many look to computers and automation as the key to improvement. However, the brilliance of the technology tends to obscure the importance of articulating precisely what kind of flexibility is necessary and defining a strategy for achieving it. The bulk of lessons learned from industry efforts at flexibility improvement via computer integration indicate that success depends more on people than any technical factor.

We know for certain that experienced teams can handle a wider range of tasks than novice teams, but even experienced teams can have difficulty adapting to change. In particular, leadership appears to play a key role in identifying the kind of flexibility needed and when it is appropriate. This is fundamental in a practical approach to automation. What seems most promising, for improved flexibility, is not automation to replace people, but automation that helps people in tailoring systems and procedures to the changing conditions. To that end, it is essential to have direct involvement by experienced mission teams in surface ship design and development.

CHAPTER 1

INTRODUCTION

A number of difficulties must be overcome to meet the emerging challenges of the 21st century. First, we face an era of austerity and change as US forces are downsized. We also face many uncertainties due to the diversity of threats and environments that must be expected in future joint and expeditionary warfare operations. At the same time, we must recognize that this is an era of rapid change in warfare systems and methods. The mix of capability, versatility, and affordability characteristics envisioned for new combatants will call for new levels of engineering achievement. Given the complexity of warships, this demands nothing less than a comprehensive reengineering of the process by which operational requirements are transformed into new combatants. Both problems of current practice and emerging opportunities must be considered in framing this task.

EVOLUTION OF THE SHIP ACQUISITION PROCESS

Today's ship design, acquisition, and construction process is the end result of a long evolutionary chain. The overall structure of the process, its history, and the underlying concept of organization are considered in References 1 through 17. Over the years, the Navy has experimented with many different approaches to ship design, as shown especially in References 2, 3, 14, and 17. Stovepiping* and the growing complexity of modern systems have been important concerns throughout this period.

Ship design and acquisition functions were managed in much the same way from the 1920s until about 1966. Ship design functions were performed in house and some construction was also performed in house, at naval shipyards. Feasibility studies, preliminary design, and contract design were done by the Bureau of Ships (BUSHIPS) design division. The problem of managing ship construction was then turned over to a type desk, which handled all ships of a particular type, such as destroyers. BUSHIPS had been formed by merging the Bureau of Construction and Repair with the Bureau of Engineering in 1940 and was fairly stable from 1940 to 1958. The first major reorganization took place with the DoD Reorganization Act of 1958. Reference 1 states that one of the key objectives was to "...complete evolution of the Ship Design

* The purpose of a stovepipe, in conventional usage, is to separate the exhaust gas flows from the other air flows around a stove. By analogy, a process is said to be *stovepiped* when it is isolated from other, similar processes. Use of the term suggests a lack of proper coordination.

organization along functional lines." The idea was to bring the machinery and electronics disciplines into preliminary design, which until then had remained a naval architecture preserve. The Bureau of Weapons was also formed at this time, by merging the Bureau of Ordnance and the Bureau of Aeronautics. Both changes were intended to deal with stovepiping concerns.

The advent of total package procurement in the mid-1960s brought further changes to the ship design, acquisition, and construction process. Following a critical review of ship design and integration procedures by the National Academy of Sciences in 1966, a project management approach was introduced for the LHA, DD 963, and CGN 38 programs. The total package procurement policy led to use of private shipbuilders for design of these ship classes. In addition, the use of public shipyards for new construction was eliminated.

1970 brought a return to in-house ship design with a central design management organization in the Naval Ship Engineering Center (NAVSEC). Total package procurement came to an end because it was difficult to stabilize requirements, the process was vulnerable to buy-in, and the most cost-effective solution too often turned out to be one with a very high unit acquisition cost. Although ship design was brought into NAVSEC, the USS PERRY Class (FFG 7) became the first design-to-cost ship.

RETURN TO TOTAL SHIP ENGINEERING

A growing Soviet naval threat, together with a series of controversial shipbuilding claims, led to formulation of a new Naval Sea Systems Command (NAVSEA) ship design strategy for the 1980s. Acquisition streamlining became a major theme for the decade, a trend which continued into the 90s with commercialization and Defense Acquisition Reform. However, NAVSEA concluded in 1986 that the necessary level of total ship engineering had not been reached. Similar conclusions were reached in two 1988 studies (see References 10 and 11). The conclusions are illustrated by a comparison between USS FLETCHER (DD 445) and USS ARLEIGH BURKE (DDG 51) classes of destroyers. Though separated by 50 years, both designs reflect the idea that a warship should be regarded as a weapon system (every part contributing to ordnance on target). But many designs produced in the intervening 50 years did not achieve the same quality of integration, and even in DDG 51, major advances were noted only in fire control.

Both ships and aircraft are used to carry and operate combat systems, both have commercial counterparts, and both involve fluid dynamics and structures. Hence comparisons are often drawn. But we don't buy ships and aircraft in the same way. We buy ships more like buildings: we get an architect to design what we think we want, choose a builder, and construct relatively few units to any given design (10 versus 100). At its worst, this approach can mean buying combat systems somewhat like furniture, as something that adds little real value to the building but makes it easier to attract tenants. At best it turns into what may be called the bottom-up approach. Given a desired set of combat systems, the ship design team proceeds to wrap a suitable hull around it and stuff all of the necessary machinery and accommodations inside. The combat systems are treated as government-furnished equipment (GFE) items provided by an array of largely independent programs. Construction proceeds from the keel up by a process of component assembly and integration. Total ship engineering, in this context, means ensuring that appropriate ship elements are selected and effectively and efficiently combined to meet design requirements. The ship designers serve as integration agents, providing the physical interfaces (spatial, mechanical, and electrical) necessary to package stand-alone component systems into the hull. Operator interfaces are determined by the GFE installed, and little attention is given to integration across mission area lines. As in the domain of buildings, none of the parties involved has a strong incentive to maintain an R&D capability, so efforts to develop and apply ship technologies are hampered. In addition, the bottom-up approach is costly in terms of acquisition, manning, and logistics support.

DEALING WITH COST FACTORS

With respect to cost, the problem is that none of the parties involved has a real grip on total acquisition cost (end cost). The NAVSEA Chief Engineer in June 1990 initiated an effort to improve quality of future ship designs, to reduce ship construction and life cycle costs, and to reduce time required to deliver the lead ship of a class. Results[14] suggest there is limited potential for reducing end cost (total acquisition cost) by changes in the shipbuilding process alone. In modern warships the combat system may account for 60 percent or more of end cost. Handled as GFE, this part of end cost is not under a shipbuilder's direct control. Planning and change orders accounting for another 15 to 25 percent are outside the builder's direct control. Perhaps only about 15 percent of end cost can be leveraged by changes in the shipbuilding process.

What is needed is a disciplined system engineering approach in which affordability and capability are considered as two sides of the same coin (i.e., a strong Fleet). Such a strategy is outlined in Figure 1. The pie chart applies to life cycle cost (LCC) for a typical ship as given by Reference 18. The pieces will vary in relative size for each ship type and class. One of the larger pieces, personnel cost, can be addressed by automation and by process reengineering. Although the original data applies to the ship's crew, it should be recognized that ashore personnel costs are also a major contributor. Other areas can be addressed by exploiting commercial products and by reinventing development and support processes. While improved productivity in shipbuilding and construction should be sought, broad gains can be achieved only by considering the entire value stream.*

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* A process involves a group of activities working together to supply a good or service. Each activity performs some function on a set of inputs in order to add something to the value of the good or service delivered. Ordered by completion time, the activities associated with a given process can be thought of as a sequence of value-adding steps, or a stream of values.

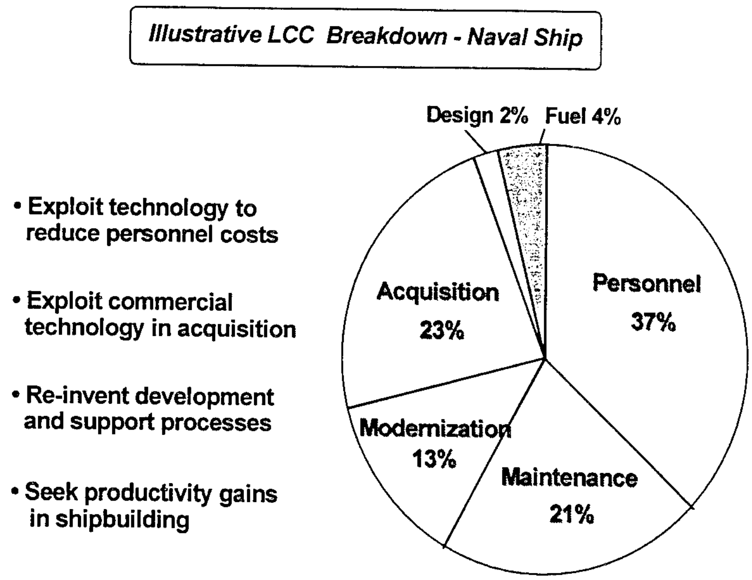

FIGURE 1. STRATEGY FOR AFFORDABILITY

In particular, combat capabilities continue to have an important place in the overall value stream. The progress noted by Reference 10 was achieved only by great effort, but many believe the era of rapid and fundamental change in warfighting systems and methods we now face will require much greater effort. Surface combatants carry a mix of weapon systems, usually developed by different programs to different protocols and standards, and creation of a well-integrated combat system involves a major effort. In fact, the effort necessary to create unique integration solutions for each ship type and class (CVN, LX, DD) may now be unaffordable. Further, modernization is difficult: the ability to add or change interfaces eventually becomes a bottleneck to change and upgrade. Recently the House Appropriations Committee[19] identified the Navy as the slowest of the services to recognize the opportunities available from the ongoing revolution of computer and software technology. It was asserted that many opportunities to reduce costs and to improve the effectiveness of Navy operations are missed through ineffective application of computer technology.

TRENDS IN WARSHIP DEVELOPMENT

A quick review of important trends will indicate why lack of clear incentives for warship R&D is a problem. Major trends include formulation of new concepts for achieving modularity in warships and Fleets and extending the concept of survivability to include signature reduction.

Achieving Modularity

The idea of a ship built for modularity was studied by NAVSEA during the 1970s, in the SEAMOD Project,[8] and physically realized by the MEKO line of warships in the 1980s. Generally speaking, ship and combat system design processes are closely coupled in traditional designs. Physical characteristics and interface requirements of combat system components must be relatively well defined before the ship design phase begins, and the resulting design accommodates only the specified combat suite. The problem is to make the interfaces between ship and combat system elements predictable. The use of standard interfaces was seen as a possible solution. Decoupling ship and combat system design processes could permit concurrent design efforts and make upgrades easier. This led to the idea of a variable payload ship.[5] The difficulty of an evolutionary approach to implementation may be the biggest drawback of this concept. Application of the basic idea to selected modules such as the Mk 41 Vertical Launching System (VLS), however, has enjoyed considerable success. Today the Affordability Through Commonality program[20] has been established to develop modular designs for selected components. Standards will be defined for module size, weight, center of gravity, environmental testing, interfaces, and the like in order to optimize commonality and reduce logistic support costs. Many of the modules being considered are ship systems rather than combat systems.

Since existing aircraft carriers can be viewed as variable payload ships, modularity can also be sought by building the warfighting capabilities into embarked vehicles (or mission teams). The basic idea involves the use of a large ship to reach the operating area and smaller vehicles to deliver ordnance. In effect this gives a two-stage warfighting system. The embarked vehicles need not be fixed wing aircraft: surface vessels, helicopters, and unmanned vehicles can be employed. Heavy lift ships such as SS MIGHTY SERVANT have been used to carry warships and could easily be used to deliver mine countermeasures or special warfare craft to forward operating areas. However, aircraft receive the most attention. Today it is widely acknowledged that embarked air assets are essential for a balanced multiwarfare combatant. The success of LAMPS motivates greater use of helicopters. Unmanned air vehicles may find use in minefield reconnaissance, general surveillance, and battle damage assessment roles. These trends raise new design issues with respect to tasking authority, time to change mission modules, and allocation of resources for joint and expeditionary warfare operations. The concept of mobile sea bases envisioned in Reference 21 combines both approaches to modularity.

Survivability

Warship survivability depends on a total ship approach. Firepower and stealth influence survivability by reducing the probability of a hit. Many systems influence a ship's capability to survive a hit and fight hurt. Hits result in complex damage effects that must be rapidly diagnosed, prioritized, and then repaired. Critical spaces are subject to damage from fire or flooding; power and propulsion systems may be out of commission and fire mains cut; weapons may be damaged and people injured or killed.

Automated damage control coordination is needed to gather status data, interpret it, and determine priorities for repair action. The key may be to design for early integration of critical systems on a total ship basis, using a survivable interconnection network for data, voice, imagery, video, power, and control of signal distribution.

Current interest in signature reduction has major implications for ship design strategies. Signature reduction involves a new set of parameters linking ship systems directly to warfighting effectiveness. Embarked helicopters or unmanned aerial vehicles (UAVs), towed bodies, and replenishment operations all make demands on topside access and can create windows of vulnerability by energy release as well as reflection of incident signal energy. The continuing competition for topside space is also exacerbated by the shifting character of design trades. For example, consider the trades between hard kill, soft kill, and ship signature. Ways to achieve a given level of improvement in self-defense capability include hotter missiles, improved electronic countermeasures, and reduced signature. Each, however, has different implications for sensor design and allocation of topside space. In addition, any shift away from active defense capabilities tends to raise force structure issues.

FINDING A PRACTICAL APPROACH

Each of these concepts involves different ways of arriving at a ship's general physical arrangement and breakdown into modules for construction. Each demands an approach to design that cuts across the traditional breakdown into combat and ship systems. The difficulty is that no one individual can deal adequately with complex systems across all relevant levels of concern. Even the Manhattan project, the Tennessee Valley Authority, and the system of mass production invented by Henry Ford had limits. Many attempts to design and integrate megasystems, wrapping multiple requirements into one solution, have run into severe technical and organizational problems. Accordingly, many believe that a modular or building block approach is the only intelligent way to build large, integrated systems. The "humpty-dumpty" phenomenon makes the engineering of such systems difficult. It is all too easy to break a problem into lots of little pieces. But if the partitioning approach is not carefully chosen, all the king's horses and all the king's men will not be able to weave the pieces into the coherent warfighting system necessary for effective naval operations. For successful integration, each module added to the system must interact smoothly with modules already in place. Articulating a practical approach to total ship system engineering is thus a key step toward equipping the Navy of the future with modern, affordable, and effective surface ships. The best practices of aircraft, construction, and other industries should be reflected in the chosen approach, consistent with the practical lessons learned from many decades of naval operations.

CHAPTER 2

SYSTEM ENGINEERING ON A TOTAL SHIP BASIS

SYSTEM ENGINEERING BASICS

A system is a set of components interacting in some organized way to achieve a common purpose. At the core of every system is a control process that governs how inputs are transformed into outputs. System engineering is a robust approach to the design, creation, and operation of complex systems. In essence, it serves as a transmitter for innovation, intended to meet two critical needs. First, new ideas (signals from some master source) are modulated and amplified into programs matched to the practical needs of some large operating system (or market). Second, the needs of the operating system are coupled to the process of technical innovation, transmitting a sense of purpose and discipline that are critically important for effective management of engineering effort. System engineering encompasses efforts to identify and quantify system goals, create alternative system design concepts, perform trade studies, select and implement the best design, verify that the design is actually built and properly integrated, and then to assess how well the system goals are met. As part of its role in verification, system engineering controls the technical baselines of the system (typically including functional, design-to, build-to, as-built, and as-deployed baselines) and must ensure an efficient and logical progression through these baselines. System decomposition and design are then pursued through the creation of design-to specifications for all major end items. Design engineering activities follow with development of detailed engineering designs which comply with the approved design-to baseline. System engineering also audits design solutions for compliance to the higher-level baselines.

There are five core activities in system engineering: requirements definition, functional analysis, synthesis, evaluation, and description of product elements. The flow of work is iterative, with successively finer resolution of system design definition on each pass. Overall, there are two stages, as shown in Figure 2: first, definition and decomposition; second, integration and verification. The aim of work in the first stage is to select a preferred design approach. System requirements are progressively decomposed into baselines for subsystems, elements, components, and assemblies until the lowest level of resources (hardware parts or software units) is specified. The core problem is not simply to divide and conquer; decomposition must be guided by a strategy for integrating the subsystems into an overall solution. The challenge is to decompose tasks and to allocate subtasks without compromising the wholeness of the task. When viewed from this perspective, it becomes clear that theories and analysis

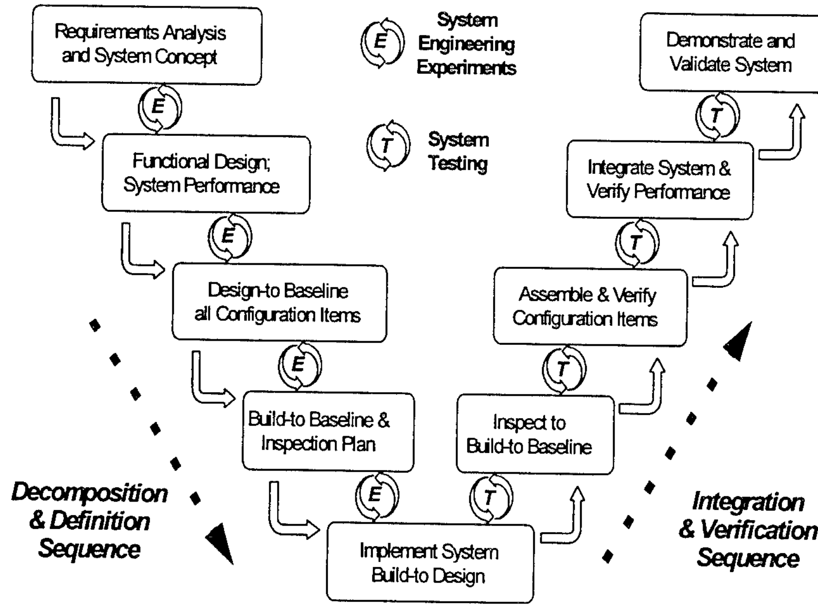

FIGURE 2. FLOW OF WORK IN SYSTEM ENGINEERING

tools are needed for representing the problem both as a whole and as a set of interdependent subproblems.

Once a preferred design approach is chosen, it is tested in the second stage by reversing (unwinding) the decomposition to verify that system expectations and requirements are met. However, activities of the two sequences are in close correspondence: verification methods, for example, determined as system requirements are decomposed and documented at each level of resolution. Prototyping and engineering experiments offer considerable scope for working the two sequences in parallel at a given level of resolution, in order to generate information needed for development. When applied to system architecture definition, integration and verification activity may be called *system conceptual integration* and occurs in all phases of the acquisition cycle. *System physical integration,* in contrast, occurs primarily in the late stages of construction as production items are delivered and installed. The delivered hardware parts and software units are formed into higher and higher levels of assembly until a complete, functioning system is achieved. With the exception of lead ship production efforts, the aim here is not to generate information needed to specify or verify a design but rather to assemble a system from previously verified component designs.

ARTICULATING A NEW PROCESS

The next step is to articulate how system engineering may be applied to surface combatants on a total ship basis. A suitable process must integrate ship design, construction, and support activities over the entire value stream. This makes total ship system engineering as much a process control or coordination problem as it is a technical problem. By eliminating unnecessary steps, aligning all steps in a continuous flow, recombining labor into cross-functional teams, and continually striving for improvement, more capable and affordable ships can be produced. Ships can also be made more flexible and responsive to user needs.

But this is not the end of the road to improvement. Many activities add value to surface ships, and their net value to the nation's defense can be raised dramatically if individual breakthroughs can be linked up and down the value chain. Maximum net value can be achieved only if the activities involved can work together as a team. The chief concern in process design is to ensure that all major design decisions are based on what's best for the ship as a whole, rather than what's best for any particular component system or class of systems. For this, three things are necessary:

- *A culture of teamwork permitting a unified system engineering effort*
- *A common framework for total ship system engineering*
- *Agreed-to concepts, standards, and tools for design integration*

The root concern is to ensure that future naval forces are capable of executing a chosen concept of operations against a capable and determined adversary.

CULTURE OF TEAMWORK

Achieving cooperation within the value stream is difficult because the component activities have needs that conflict with those of the value stream. Every stream needs a team leader that orchestrates the decision to form an enterprise, pulls together the full complement of members, and leads the joint analysis of the total enterprise stream. Unfortunately, this leadership position is easily used to extract advantage from upstream and downstream partners. If component activities are to work together effectively, a culture of teamwork must be established. Formation of a system engineering cadre able to consider tradeoffs from a total ship point of view may be the most crucial factor in establishing such a disciplined management approach. A possible strategy for cadre formation might proceed as follows:

- Create a top-level, process definition team

- Form a technical cadre, trained to a common framework and lexicon

- Organize this cadre into a small number of teams, each to address integrated design concepts, standards, and tools for a selected core subsystem.

Partitioning the overall control problem into a small number of backbone areas (or core subsystems) is a critical step in establishing a culture of teamwork. A decision must be made very early in the system definition process, and it is all too easy to find convenient pieces without establishing clearly how they will work together to form a well-integrated operating entity. It is critical at this point to provide a framework for defining and controlling how the corresponding teams can achieve a unity of effort in system engineering. A basic control structure, provision for resource sharing among subsystems, and a workable approach to change and upgrade actions must all be articulated at this point. Adequacy of the engineering process depends on what it takes to make these decisions. Proposals for a virtual enterprise, in which contributors come and go (plug and play fashion), fail to grasp the massive costs of the casual interactions involved. Such arrangements may work for emerging industries in which product specification and market demand are subject to dramatic and unpredictable change, but they are terrible for the vast majority of activities.

Hostile relationships among the component activities cannot be ended simply by trust. Practical arrangements must be rooted in agreed principles of just behavior and procedures that enable each party to verify that others are keeping their end of the deal. The component activities in a stream must discuss the total activity, performance requirements for individual activities, performance verification procedures, and reward formulas.

COMMON FRAMEWORK

For a large composite system such as a ship, dealing with component systems one by one is not good enough. A better approach is needed, one that permits coordination of many independent projects to create a fully integrated system of systems. Such an approach is considered in References 22 through 27. The basic idea is that total ship system engineering involves a hierarchy of design levels and that systems at any one level are embedded in successively higher level systems that address discrete operating tasks, individual mission areas, ship characteristics, and ultimately national systems that transcend even the specific military purpose of DoD. For example, a radar might be considered a component of an air defense system, air defense part of the nation's defense system, which in turn is part of the Joint Chiefs of Staff-managed military system. That system then must operate within a national system that includes others such as the air traffic control system.

A system of systems is one that is formed by integrating other systems, each a product in its own right and with its own development sites, objectives, management, and schedule. In many cases, component systems are taken off the shelf and integration must proceed in a bottom-up manner. Since complete systems, rather than subsystems or modules, must be integrated, system integration is more difficult than usual. Not only are the components to be integrated more complex, but each may have its own standards, and it can be difficult to understand behavior of the overall system. The overall system may be general purpose or specialized. The flight control system for a jumbo jet is an example of the latter type, which may be large and complex but is intended to solve a particular problem in a given time frame. Surface ships are an example of the former type, which operate in a given application domain but are multipurpose and must be flexible as to the time, place, and circumstances of use. While the same idea is present in the proverb relating loss of a kingdom to loss of a horse shoe nail, first use of this term may be due to John Jacobs.[28]

Since development of a system of systems usually involves people working at multiple sites, with different management teams and procedures, communication problems are likely to occur. To solve the communication problems, much more emphasis on definition of interfaces and specifications is required. However, considering specification of interfaces only does not ensure that required operations are done in the required order and manner. Required behavior must be specified as with traditional systems, but now the problem is even more complicated. Required behavior must be specified not only for component systems, but also for the overall system.

Because of the dynamics and the relatively long time frame involved in this kind of development, requirements analysis cannot be done as a specific step at the beginning of the development process. New methods and processes must be defined to cope with the specific problems of this category of systems. Use of a generic framework, dividing the overall effort into several projects and two levels of management, is suggested. Figure 3 shows such a framework. One level provides coordination for the overall system, working across projects, while the other manages individual projects. Establishment of this framework begins with domain analysis, to establish a basis for specifying requirements. Infrastructure and integration architecture are used to enable integration of component systems into a consistent overall system in an efficient way.

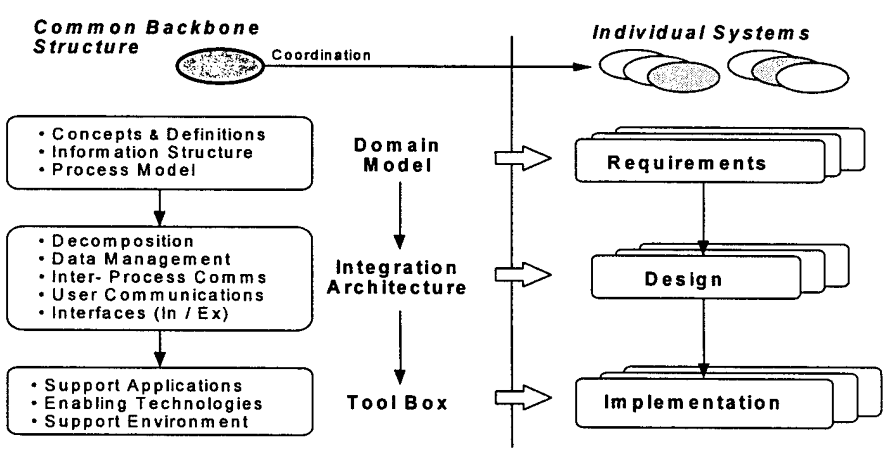

FIGURE 3. SYSTEMS OF SYSTEMS ENGINEERING FRAMEWORK

MECHANISMS FOR DESIGN INTEGRATION

Design integration involves all engineering necessary to fully integrate the component systems. Key responsibilities include defining system top-level functional capabilities, assuring intersystem performance, and verifying that there is an integrated architecture in distinction to a random collection of subsystems that have somehow been put together and barely interoperate. Indeed, the purpose of this activity is to optimize overall system performance, despite the fact that component systems were developed under quite different conditions and ground rules. It is the single point at which overall system integrity is examined in order to maintain or improve performance. Software has been and likely will continue to be the most difficult and high risk aspect in acquisition of large-scale systems. Configuration management is also a significant problem in that the different schemes under which individual systems were developed must be integrated to the maximum extent possible. This is necessary to provide in-service support for the overall system.

System of systems engineering involves two kinds of integration, one that focuses on mechanisms used to interconnect parts and another that focuses on the uniformity of an overall system design. A dictionary definition of the term integration, "make whole or complete by bringing together parts," succinctly captures this tension between the parts and the whole. On the one hand, we talk about a system, a whole or complete thing; on the other, we talk about bringing together parts. The system side of the equation emphasizes global system properties; e.g., the harmonious "look and feel" of user interfaces, or the linguistic elegance of system structure. The parts side of the equation emphasizes interconnection and interoperation; e.g., interoperability of functions, data files, and subsystems.

These two kinds of integration reflect different development processes. When a system is designed before its components are designed and built, we speak of pre-facto integration. If the parts are designed and built before the system is designed, or even conceived of, we speak of post-facto integration.

The two types of integration come together in the phased, top-down approach discussed in References 22 and 25. Large and complex systems tend to make system development and integration a highly complex process, requiring flexible but firm management that takes future changes in requirements and technology into consideration from the beginning. Requirements of large and complex systems are inherently incomplete and have a tendency to change. Requirements are seen only as a starting point, subject to change on agreement by the user and developer, and this makes system integration even more complex. Typical acquisition processes demand quick decisions, influencing the future integration structure in unpredictable ways and leading to design errors that are hard to correct. To overcome these difficulties, system development and integration is divided into two phases, archetyping and actual system building. The two phases are independent and archetyping is the topic of interest here. It is split into two steps, architecting and prototyping.

Architecting uses a top-level design approach to construct a model of the system. Such a generic model (integration architecture) allows integration of already existing components and provides a framework for interface definition, performance assessment, and cost evaluation. However, the model should be generic and robust enough to provide flexibility and adaptivity for changes in requirements and technologies. Sensitivity analysis and simulation are suggested for use in this stage to obtain reliable results.

The prototyping step of the archetyping phase is used to construct an architected and tested demonstration prototype of the system. This prototype is then used to verify the architecture and to check the assumptions made in the architecting step. Actual system building, following archetyping, is a relatively conventional phase, based on the principles of system engineering. Besides the technical part, it includes monitoring of progress, user training, and verifying assumptions (e.g., about system performance) made in the archetyping phase. This phase always follows archetyping and can be performed either by in-house development of the integrated system or by an external contractor. In both cases, developers have to work according to the results of the preceding archetyping phase. This phased, top-down approach includes the three dimensions of enabling technologies, integration architecture, and global integration. In its architecting step, it defines an integration architecture and addresses global integration issues without binding the system too early to existing solutions and technologies. This makes the architecting phase a critical step that has to be supported properly by methods, reference architectures, standards, and tools.

Role of Integration Architecture

Integration architecture is the core of this framework. Architecture is a logical construct for defining and controlling the system engineering process. Its definition begins with a structure (partitioning) and control strategy enabling all parts of the system to work smoothly together in performing mission tasks. In particular, the architecture concept should include an extension framework and be subject to formal change control from the earliest stages of development. What is common to all types of integration architectures is a decomposition into two main parts, the conceptual model and the technical infrastructure. The first links the domain analysis to the infrastructure created to support development. The second provides the standardized services necessary to ensure that all projects in the domain can rely on a standard implementation platform. These services must be developed and maintained as part of a separate project above the level of individual system efforts. This provides the support environment for implementing an individual system following the rules of the conceptual model. Once specified, the integration architecture becomes the basis for all other decision processes regarding system development in the domain of interest.

The concept of integration architectures refers to the idea that an integrated system should have a strategically chosen open architecture, implemented on the basis of identified enabling technologies. An integration architecture, like a system specification for an individual project, serves as a general pattern or blueprint for defining the basic layout of an integrated system. Grounded in domain analysis, it must indicate how all parts of the overall system can work smoothly together to accomplish mission tasks. In particular, it provides a general strategy for system decomposition, data storage, interprocess and user communications, and the handling of internal and external interfaces. Changes should be placed under control from the first stages of development, and an extension framework identified. Further, guidelines (principles or metarules for system design) and standards should be provided for the design of individual systems and the bottom-up integration of partial solutions that already exist. From a global view of the domain, the integration architecture functions like a strategic planning scheme for the overall organization by (a) pointing out key directions and tradeoffs for design, (b) ensuring that individual projects contribute to goals of the overall system, and (c) ensuring compatibility and communication among all ongoing efforts. Once specified, it becomes the basis for all other decision processes regarding system development in the domain.

Hardware architectures fill the job of a generic and standardized blueprint for different models of one machine architecture. As with hardware architectures, integration architectures serve as generic blueprints for the management of complex systems. They deal on the one hand with standards, guidelines, and domain knowledge on a conceptual level and on the other hand with the necessary environmental infrastructure like hardware, networking, operating systems, and protocols. However, working within an integration architecture means to work within boundaries. These boundaries will reduce the freedom of choice we have and will support some types of application while complicating the implementation of others.

Integration architectures have a natural place in between conceptual domain knowledge and implementation-oriented enabling technologies, which makes them a useful basis for decision processes. Domain analysis delivers a general specification for the architecture's functionality and data handling capabilities, while the infrastructure level offers a set of technologies that enable implementation of the architecture and embedded applications. A core set of tools and technologies forms the designated basis for the architecture and so merits a high priority in support and development. On top of the core technologies, development and run time environments are defined and maintained. The core set must be limited in extent, yet sufficient to support the full architecture. This simplifies relationships between the integration architecture and its enabling technologies. At the same time, the core must be reexamined on a regular basis, permitting cycles of adaptation and change to rejuvenate the architecture.

Elements of an Integration Architecture

Conceptual Layout. With regard to conceptual layout, an integration architecture does not ask for a specific form of implementation. An architecture with a common database as a basis for communication and data storage might be implemented on top of a distributed database management system (DBMS) whose characteristics are hidden from the architectural level of specification. The DBMS is used transparently. To guide this kind of implementation effort and to ensure compatibility between implementors, standards and guidelines for implementation must be defined.

Domain Model. Global integration focuses on the integrated system as a whole and not on the parts of the system. To prevent use of highly complex and incompatible data structures in different parts of the system, to preserve a common universe of discourse for users and processes, and to allow easy integration of new applications, a domain model must be defined. Based on a common universe of discourse, a generalized process model of the domain can be specified to reflect the common understanding of tasks, roles, and resources and to reflect the knowledge and standards for data processing in the chosen domain. This process model is used as a reference model on the meta level to coordinate integration activities.

Considering the immature nature of the total ship system engineering field, the first task of a process engineer is to design a process and its support elements before tool support and distinct applications are considered. Constructing a process model assures a common understanding of the application domain and the feasibility of developing a conceptual architecture. As soon as a process is defined and implemented in a supporting (tool) environment, the product engineer can handle the development of applications in an integrated manner.

The National Institute of Standards and Technology (NIST) Application Portability Profile model (see Reference 29) appears to be an instance of the approach outlined above. It is based on a concept of computing and a mapping of this concept into component and service categories. This involves an integrated view of how information is organized and used in development and application of computing resources and the specification of a generalized process model for computing operations. Domain analysis is a necessary first step in this approach. Any global definitions and standards applicable to the framework, perhaps based on prior steps toward global integration, must be considered as an influence on the architecture design.

Decomposition Strategy. The decomposition strategy provides a common pattern of thinking, describing what global system functions will be addressed by each newly developed system component. These global functions are identified from analysis of the application domain and the structure of the chosen conceptual integration architecture.

Architecture Standards. How functions are implemented is not of interest for the architecture. Essential capabilities are identified without specifying how they will be implemented. Two major issues in defining the technical aspects of integration architectures are the description of communication and data handling within the system. Standardized messages and a common global database can help to reduce the complexity of communication and data transfer. The specification of communication in an integrated system and the handling of data in the system are closely related. Systems that rely on communication via a common database are naturally implemented with a standardized central repository. Systems with distributed data handling involve an elaborated message passing concept and rely heavily on predefined and secured communication channels between components.

Guidelines for Implementation. Whereas a domain reference model defines the meta level of the integration architecture, implementation guidelines define a basis for the architecture in terms of existing methods and tools. Enabling technologies are the tool level of the framework (Figure 3) and provide elements required by the infrastructure to develop and implement individual systems that will fill the abstract architecture with functionality and data. Backbone activities should not only be concerned with the state of the art in technology but also give suggestions for standards and developments in the domain. The standards used for implementation describe the technological basis on which the generic integration architecture is implemented. A typical example is the specification of the Open Systems Interconnection (OSI) model as a basis for all communication in the architecture and for the selection of specific services to implement them. The standards for communication are specified on top of the application layer of the International Standards Organization (ISO)/OSI model. The implementation guidelines also specify hardware restrictions, programming languages, coding standards, documentation guidelines, and the like.

Types of Integration Architecture

Three types of integration architecture are found in many existing large-scale systems: (a) message passing, (b) systems with a central data repository, and (c) generic systems. In its basic layout, the message-passing approach is a variation of the object-oriented and channel-based schemes that are widely used in hardware systems. Both schemes provide sufficient flexibility, adaptability, and scalability for use in a wide range of application domains. Channel-based systems represent a form of object-oriented system, while systems with a central data repository can be viewed as a form of generic system. These three architecture concepts thus represent a unifying framework for integration of individual systems and for describing the types of individual systems that may be contained within a ship. By studying the concepts, their use in different application domains and their influence on enabling technologies, practical rules and tradeoffs can be identified and used as guidelines for total ship system engineering. Concurrent systems with message passing between processes and objects and systems linked by a common data repository are widely used for integration of multiple application systems. Furthermore, they provide approaches that can be used to create highly flexible, generic systems specifications.

An open system approach is needed for successful application of any kind of integration architecture. Specification, design, and eventually implementation details should not be proprietary information, but should be available for every interested user or vendor. An open system would have to define at least the following system parts and ideally give some freedom to modify them: basic architecture, user interface, data storage and representation, system functions, data transfer, and the enabling technologies used. As an example, Reference 30 indicates how this can be done. An open system approach seems to be feasible in terms of technical risk, user satisfaction and affordability.

Message Passing. In systems with this architecture, components exchange messages in standard format using a predefined communication system. The messages trigger component activities. This approach emphasizes the communication side of the architecture and leaves data handling to the distributed components of the system, which act like data capsules. Message-passing systems can be used easily as models for integration architectures or as a backbone for a targeted system in the integration process. A channel-based approach goes naturally with a concept of distributed data storage. A central data repository can serve as a component in this architecture, but it may trigger such problems as overloading of the channel and performance bottlenecks in the data processing.

Central Data Repository. Systems are designed with a central data repository when the main resource that has to be managed is data. This occurs often in integrated development environments, where a general model for domain information processing is used instead of a single application program. Special attention has to be paid to design of a conceptual model for the data and to development of the associated database system. In pure form, this architecture links components only through the central database. Since the database is the main integrating factor, components usually can be added or deleted without severe direct side effects on other parts of the system. A good example of this type of architecture is given by Best.[31]

Generic Systems. With integration becoming a major concern for system acquisition, increasing emphasis is being placed on systems which are generic rather than prepackaged and ready to use, but fixed in most details. A generic system has a range of operating parameters, so that appropriate values can be selected to tailor its operating characteristics for a particular application environment. Usually the system is designed to support several different patterns of use, to be implemented by choosing components from a family of items with similar functionality and layout. Methods of communicating between components are predefined in the application and supported by integrity rules describing interfaces and parameters. Strict consistency rules are necessary to ensure the components fit within the predefined application framework. Designs must permit change in patterns of use, including addition, deletion, or adaptation of functions. Most generic systems are targeted on a well-defined segment of some application domain.

Modeling and Simulation

The potential role of modeling and simulation in ship design, acquisition, and operation is considered by Cannon-Bowers[32] and Jons et al.[33] Models have been employed for thousands of years as an aid to shipbuilding. Due to advances in modern technology, computer-based models are commonly used for this purpose today. In fact, unprecedented opportunities exist for applying simulation and modeling technology to the challenge of designing, testing, and operating surface ships in the 21st century. Enormous leverage can be gained from application of such technology for idea generation, program definition, full-scale development, and production of advanced systems. Moreover, modeling and simulation can also mean major gains in training and operational flexibility for future surface ships.

Modern designers are faced with the daunting challenge of engineering warfare systems that do more with less. Simulation and modeling can play any of several roles in formation of operating concepts and design options for a new ship. First, effectiveness of a particular design can be estimated by simulation-based analysis of its performance in likely warfare scenarios. Second, studies of cost and benefit factors can be used to assess the marginal costs associated with changes or trade-offs in planned capabilities. Third, a well-developed simulation and modeling capability will allow for the forecasting of requirements and costs associated with ship personnel and resource needs, operating costs, life cycle support, logistics concerns, and training needs. Finally, the tactical roles of a proposed combatant can be investigated.

To accomplish these objectives, several technologies are applicable. First, effort devoted to developing the synthetic battlefield and synthetic theater of war are useful because they bring together a diverse set of models and simulations into a coordinated testbed. This testbed provides a rich backdrop in which potential platform capabilities and roles can be estimated. In addition, the perfection of distributed interactive simulation (DIS) technology provides for high-fidelity testing of simulated platforms interacting with both live participants and other simulated nodes. Finally, virtual technologies are maturing to the point where they can be used to assess initial human factors requirements for various design options. In this manner, users can become involved in the initial concept formation phase of total ship system engineering.

The overall impact of the capabilities afforded by simulation and modeling in design and testing is that they foster an iterative or progressive testing strategy. Through a progression of high-fidelity simulations, it is possible to refine design options, assess competing design strategies, and assess the logistic and life cycle costs associated with particular designs. This includes stimulating and evaluating various states of platform or situation degradation. Further, since simulation offers the capability to test the developing system under a variety of conditions, the limits of system performance can be assessed before development is complete. Likewise, a ship's ultimate performance can be tested more completely and under more situational and mission conditions employing high-fidelity and distributed simulations than would be possible otherwise. This can allow system users to assess many end-use concerns (e.g., safety or manning) early in the design process, thereby avoiding costly mistakes and frequent backfits once weapons are fielded. A host of human factors questions can also be investigated, including human-machine interfaces, display design, information flow, communications channels, and team coordination requirements. Simulation-based testing can, therefore, become a routine part of the design and testing cycle.

CHAPTER 3

ANALYSIS OF THE SURFACE SHIP DOMAIN

Because the US is a maritime nation, our forces must operate and fight overseas, joining with allies and coalition partners to protect our vital interests. In wartime operations, US naval forces must be able to fight and win against a capable and determined enemy. In cases short of war, US naval forces must be able to operate forward with a view to preventing conflicts and controlling crises. The problem addressed in this report is how to create affordable, capable, and usable surface ships, sufficient to execute a chosen concept for employment of naval forces in either wartime or peacetime operations. The starting point must be a clear and succinct understanding of why existing ships are designed as they are and what makes the designs valid. Accordingly, a functional reference model for surface ships is formulated below. Creating such a model and the associated vocabulary makes it easier to share ideas and accumulated knowledge throughout the Navy community. With such intellectual tools one can proceed to dissect a maritime strategy and identify its implications for how ships are designed and built.

ACCOMPLISHMENT OF MISSION TASKS

A warship is a complex of people, plant, and procedures that together form a warfighting system. The ship is only an instrument wielded by the crew to accomplish mission tasks and may be viewed as a plant for the execution of operating processes as directed by mission teams. Combatants accomplish their military purpose by delivering ordnance on target. Amphibious ships are designed to deliver landing forces for operations ashore. Replenishment ships accomplish their military purpose by delivering ammunition, fuel, and stores to the force. Each makes a vital contribution to successful warfighting operations, and requirements based on military doctrine define the operational tasks and capabilities necessary to accomplish this purpose. Each ship type is designed to support a general concept of operations, with minimum dependence on operational or implementation details that cannot be reliably foreseen.

Each operating process involves a string of discrete steps or functions, arranged to accomplish a significant mission task. Strings of these steps or functions (called action paths) are the counterpart in warships of the customer-oriented transaction loops found in commercial enterprises. As an example, Figure 4 gives functions and task flows for a notional antiair warfare action path. Rigorous definition of such action paths

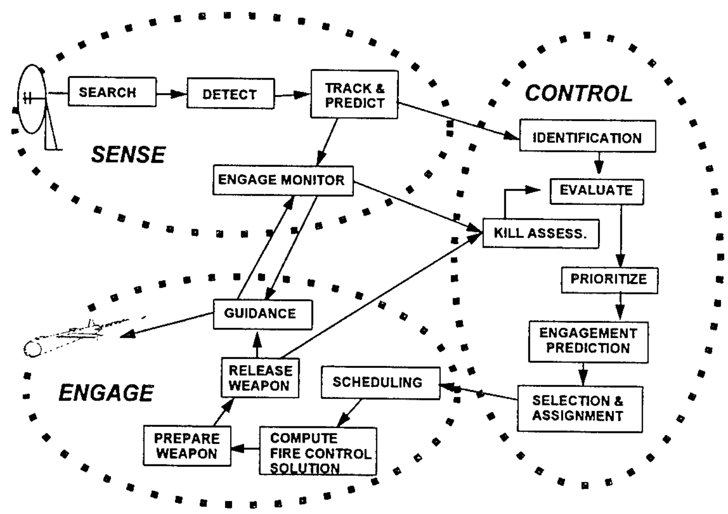

FIGURE 4. FUNCTIONS AND TASK FLOWS FOR AN ANTIAIR WARFIGHTING ACTION PATH

is a fundamental task in system design and calls for significant technical effort. Here the intent is only to group functions into sense, control, and act modules as a simplified way of describing action paths. All complex tasks involve sensing, to gather and assess relevant information; control, to assess options and allocate resources; and action, to alter the state of the ship and external entities or both by expending resources. The modules are viewed as functional rather than physical entities. For example, sensing functions in antisurface warfare action paths may be supported by an acoustic sensor intended primarily for detecting and tracking submarines.

With these conventions for describing and arranging action paths, a process model for the surface ship domain can be constructed. Surface combatants must execute a wide range of action options, as suggested by Figure 5, responsive to the will and direction of assigned mission teams. Setup, coordination, and control of action paths are the essential tasks of the command and control structure, which is designed around the mix of action paths which must be executed. Planning, training, maneuver, interaction with friendly units, and delivery of weapons against a target are examples. While individual systems generate the action paths, control structures create value by coordinating many action paths. Coordination is necessary, for example, to avoid interference and share resources across multiple action paths.

The domain reference model is framed to capture basic missions and operating concepts rather than specific details of process implementation. It must provide for definition of key concepts and a structure accommodating relationships between the

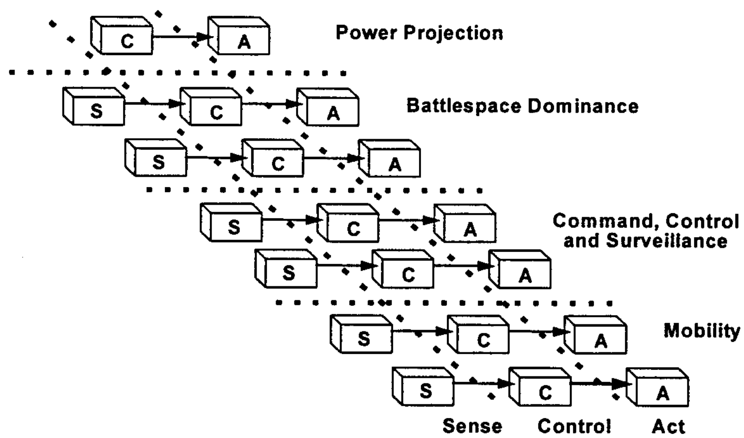

FIGURE 5. ACTION PATHS FOR SURFACE COMBATANTS

terms defined. For completeness, the relationships considered should cover all actions expected in any given operating environment. In addition, the reference model should reflect planning concepts and doctrines for the conduct of naval warfare, as they relate to the employment of surface ships.

Types of Operating Processes Executed

It is important to consider the different types of processes executed. A high-level description for any process can be formulated in terms of *entities, interactions, and systems.* A *system* is defined as a combination of human, computer, and network elements that constitute operational capabilities for the ship. *Entities* are people, machines, or events. An *interaction* is a sequence of events involving entities and systems. Surface ships support two different types of operating processes, each calling for a different approach to system design. For many systems, functionality can be described by a simple relation between initial state, inputs, and the outputs produced at some terminal state. These are called relational or transformational systems.

Most capabilities in the traditional hull, machinery and electrical (HM&E) areas are produced by relational systems. A number of examples can be given as follows. In Figure 5, suppose one of the action paths corresponds to the hull. The action modules of hull systems determine such factors as ship displacement, corrosion resistance, load bearing capacity, watertight integrity, and stability. Control resources include ballast, watertight doors, tankage, piping, and pumps. Sensing functions include determination of fluid levels, trim, reserve buoyancy, and hazards to navigation. Use of a single action path to represent all of the systems and capabilities involved makes for a simple picture, but with a modular structure that allows zooming in to a more detailed model when desired.

Returning to Figure 5, let a second action path now correspond to ship machinery. The action modules for machinery systems include pumps, engines, and transducers used to lift, steer, and propel the ship's hull and many items of supply contained within it. Sensing functions measure machine state parameters, and control functions alter those states. To complete the picture, let a third action path correspond to ship services. In particular, consider electrical power. The shipboard electrical power subsystem must sense demand load, configure appropriate paths for distribution, and generate appropriate supplies of power. Other, similar systems must generate and distribute berthing, air conditioning, compressed air, electrical power, food, potable water, chilled water, refrigeration, medical services, and other resources necessary to keep both people and machines reasonably healthy and productive. In a highly simplified way, then, the figure can be regarded as a model for ship HM&E resources.

A ship also contains many processes of a second type, which is called reactive. These processes are designed to maintain some interaction with their environment, terminating only if the system should fail. Since there is no natural terminal state, reactive processes cannot be described by a simple relation that specifies output as a function of input. Instead, they must be described in terms of ongoing behavior. Useful descriptions typically involve complex sequences of events, actions, conditions, and information flows, often with explicit timing constraints, that combine to form process overall behavior.

Both cooperative and adversarial interactions with external entities are reactive in character. A reactive process is said to be reflexive when human control is limited to supervisory functions, direct control being automated. Basic interactions involve one entity and one system and cannot be decomposed further. Composite interactions involve multiple system-entity pairings and can be decomposed into a set of basic or composite interactions, combined sequentially, simultaneously, independently, or recursively.

Target processing systems of all types are largely reactive in nature. Long-range strike makes a useful example because a centralized planning approach, with decentralized execution, is readily implemented. A relational model is appropriate to describe a typical destroyer's role in such operations, which is to generate one component of a strike in compliance with orders. But the overall strike is reactive, a fact which becomes evident when the total cycle time from detection to destruction is considered. The required interaction is accurate delivery of ordnance against a set of "targets that count." Changes in target location or background, weather conditions, and availability of target intelligence give this interaction a dynamic character. Since cycle time must eventually be reduced to deal effectively with relocatable targets, a relational model could produce systems with limited growth potential. The movement of fleets and the conduct of tactical maneuvers in meeting engagements also involve reactive processes. Figure 6 shows multiple clusters of target processing action paths, organized by warfare mission area. Figure 7 is a simplified view of a reference model for a complete combat system. The illustration is simplified by showing only a few mission areas, and only a few action paths within each mission area.

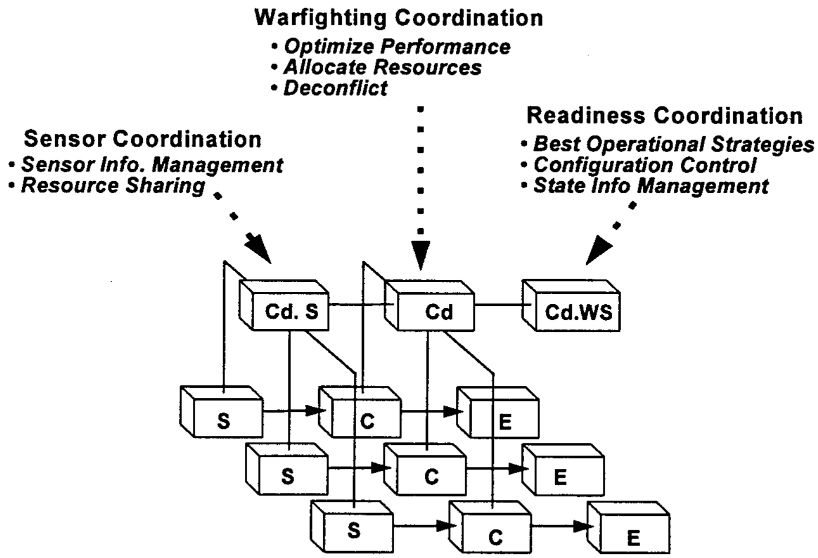

FIGURE 6. MULTIPLE ACTION PATHS IN A SINGLE WARFARE MISSION AREA

Cooperative interactions can involve external entities (friendly units) or internal entities (own ship systems and users). In this case the first set of action paths might provide for external communications and the second for internal (to include voice, video and interprocess communications). A third set of action paths corresponds to informal communications, not only interpersonal voice and visual but also those associated with command presence as well. This appears sufficient to establish a notional reference model for cooperative interactions, similar to those given for relational and target processing capabilities above. However, such tasks as formation maneuvering, cooperative engagement, and replenishment may also be considered.

Air, surface, and undersea vehicles of various types can also be operated from surface ships. Associated processes mirror the breakdown of shipboard processes. Preparation for launch, launch, and transit processes are largely relational in character. Reactive processes are generated in such tasks as payload delivery and landing.

Layered Network of Modules

Figure 7 shows the reference model as a network of modules arranged in three layers. The first layer (bottom) consists of action paths shown as strings of functional modules (Sense, Control, Act). The second layer (middle) provides for coordination of mission areas, each formed on a set of action paths grouped by task category, plus an appropriate set of coordination (Cd) functions. This permits separate coordination and control functions in each mission area so that simultaneous multiwarfare operations can

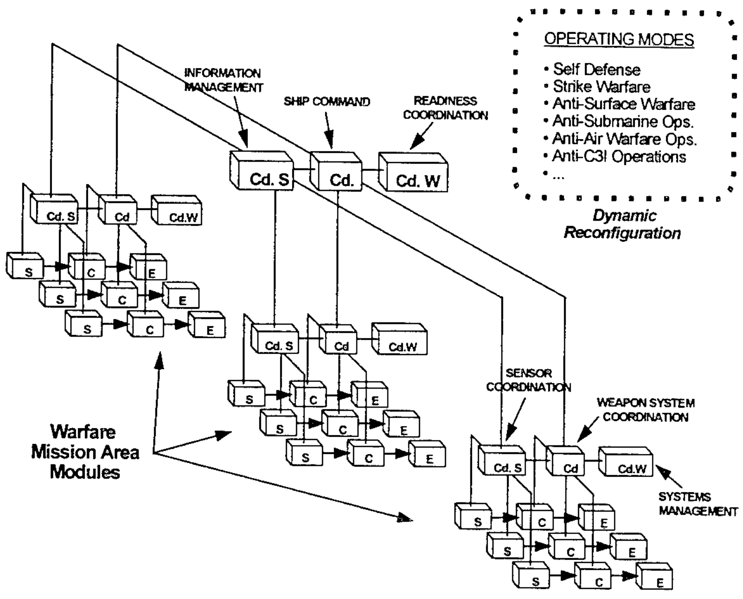

FIGURE 7. COMBAT SYSTEM FUNCTIONAL REFERENCE MODEL

be conducted. Action paths can be grouped in many different ways with little effect on the conceptual framework. The third layer (top) is the unit command level, where objectives are established and resources assigned to coordinate their accomplishment. Within each layer, functional requirements are divided into the following components:

- Task Coordination--Improves overall mission performance by coordinating action paths to avoid waste and interference

- Information Coordination--Supports handling archival as well as tactical information, including communications with higher command authorities and cooperating tactical units. Information is inherently a shareable resource and offers many opportunities for improved performance through cueing, fire coordination, or resource management.

- Resource Coordination--Includes key setup functions in the mission areas (e.g., resource allocation) that establish which of the realizable action paths are active and ready. Performance gains can also be sought by sharing components between action paths or systems. The basic idea is to allow any-to-any interconnection of functional components. For example, the primary sensor of one weapon system might be used to support secondary or backup sensing functions of another weapon system. Examples can be constructed in such areas as flight operations, configuration control, and training.

Both information and resource coordination are subordinate to the task coordination function. These functions can be allocated to different individuals if necessary to ensure the task coordinator is not overburdened. Figure 8 shows the reference model extended to the total ship level. The approach is based on Reference 34. The broad mission areas shown represent the combat, HM&E, and C^3I categories of action paths. In the HM&E category, the S - D - L path represents electrical systems, which must Sense demand and Distribute energy to Load centers. The R - D - A path represents a generic resource management loop which must generate a Resource, control its Distribution, and support end user Access. In the C^3I category, the R - P - T path corresponds to sensor Receive, Processing, and Tracking. The I - P - O path represents Input, Processing, and Output by computing systems. The R - P - S path represents message Receive, Process, and Storage by a communications system. The examples are given only to indicate the variety of functions which can be accommodated by the sense - control - act paradigm.

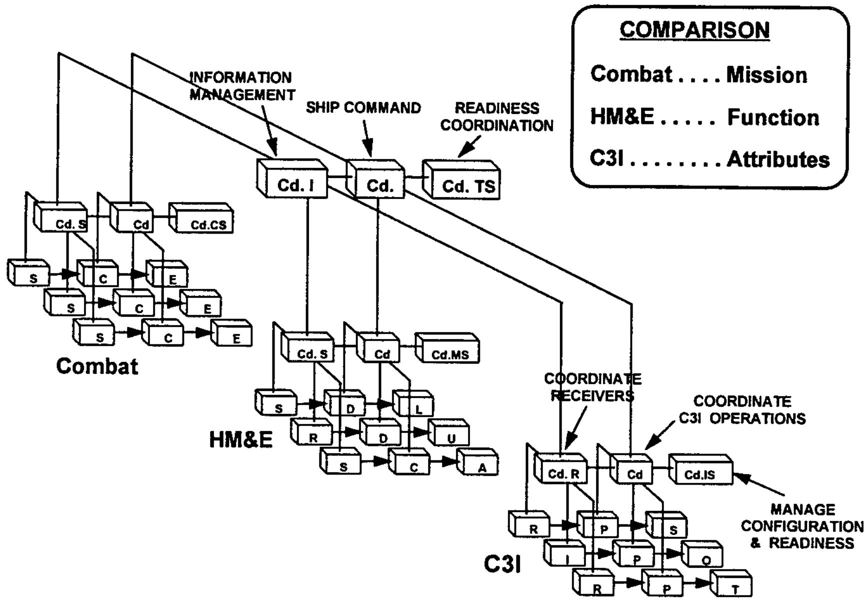

FIGURE 8. TOTAL SHIP FUNCTIONAL REFERENCE MODEL

As suggested by Figures 7 and 8, not only action paths but also information and command paths are found in warships. Information paths form the interconnection structure for data flows within the ship. Command paths form the command hierarchy, projecting command authority throughout the ship. The information and command paths create a potential for information and resource sharing which is essential to integration and affordability characteristics of future ships.

INFORMATION STRUCTURES

The structure of mission information flows is driven by decisions about ship battle organization and operational roles of the watch standers. However made, these decisions support three principal objectives. The first is to support the making of information decisions by structuring flows of information and advice to the commander. The second is to support operational decision making by structuring the flows of information among the mission teams. The third is to aid execution of operational decisions by establishing a chain of command. In particular, the necessary decisions and the watch standers who make them must be identified. The existence of three distinct aims in organizational decision making leads to creation of three distinct control path types in the control structure. Presence of the different path types has great importance for the integration and affordability properties of the combatant.

On the information (input) side of their decision making, watch standers want to tap whatever sources can provide needed information without being at the mercy of a single source for any particular kind of information. To support this aim, two types of control paths are created. Command paths support the aim of structuring the flow of information and advice to the commander from on-board and off-board sources. They also project command authority throughout the ship, providing for two-way flow of orders and status reports. One implication of the hierarchical approach is that work unit structure determines the subordinates to whom orders will be directed. Although the decisions made at each echelon are intended to direct operations at the scene of action, orders are normally directed for action to personnel only at the next lower echelon.

Information paths structure the flow of information among task teams, from sensing resources (including communications) to watch standers. For off-board sources, the operational chain of command will also define the chain for validating and prioritizing information requirements; when the operational chain of command changes, so does the path for seeking information support. Because information can be shared across different locations, information paths also knit shipboard task teams into the joint-force command structure. Accordingly, flexibility in forming information flow paths is important for future ships.

On the execution (output) side, the objective of organizational decisions usually is to achieve unity of effort in the execution of decisions. How a commander thinks that unity of effort depends on unity of command will be reflected in how the commanding officer and tactical action officer are linked to individual action paths. In practice, the mission-oriented control structure must support two sets of tasks, warfighting coordination and readiness coordination. The first provides supervisory control of tactical operations and definition of task objectives for subordinate mission areas. Related tasks include implementation of command doctrine to detect, localize, and track targets; threat evaluation; and maintaining a tactical picture. The objective in readiness coordination is to balance resources against tasks, equalizing stress on all parts of the organization. This entails (a) loading and balance controls for key operating tasks and (b) resource management and configuration controls. Associated tasks include resource allocation and monitoring in each subordinate mission area, establishing which of all possible action paths are ready for use.

CONTROL STRUCTURES

Ship control structures are strongly influenced by two factors: mission tasks and available technology. Since industrial controls respond to the same technical trends, it is worthwhile to take an occasional look at the path followed by industry. A design strategy called Dynamic Process Control evolved during the 1960s, and with its formulation in Reference 35 came to be accepted as the dominant approach to control systems. Control actions were divided into two categories, those needed to achieve material balance control throughout the plant and those needed to maintain product quality control for each individual processing unit. The former was necessary for plant management in the presence of low-frequency changes like production scheduling and could be designed separately from the latter, which was intended to regulate high frequency disturbances entering the various units. In simple terms, overdesign margins, storage buffers, and load smoothing were used to keep loading and balance controls simple. Designers were thus able to focus on controls for the individual operating units. This gives a bottom-up design approach similar to that used by the Navy.

This strategy worked very well until new economic constraints came into play. First, shortages of raw materials and energy appeared. These shortages led to new integrated designs with better energy management and more use of recycle flows in a plant. Second, restrictions appeared on fixed capital budgets. The reduced budgets led to lean processing units, with very small overdesign margins, and elimination of storage buffers. Plant operating units came to be tightly coupled via energy recovery systems and recycle flows. Thus it became necessary to address control structures for entire plants, rather than individual operating units. The complete plant approach is outlined in References 36 and 37.

Adapting to reduced capital budgets is clearly important for the surface ships domain. Energy management and recycle flows are less important, but the problem of rationalizing information flows presents a similar set of problems. Overall, it appears that surface ship design, acquisition, and construction may benefit from process improvements as much as other enterprises have done. As Reference 38 suggests, an era of fundamental change in productive systems and methods is now under way. Leading commercial enterprises now envision a system of tightly integrated loops connecting all key parties to a transaction (customer, producer, distributor and payment agency). Underpinning these loops will be systems of lean production that use less of everything compared with the mass production systems of the past: half the human effort in half the space, and half the engineering effort to develop new products in half the time. Plants will be designed to gain efficiency levels bordering on perfection and to achieve high product variety with continually declining costs, zero defects, and zero inventories. Virtually every enterprise that depends on large and complex productive systems is exploring ways to pursue a similar vision. The call for total ship system engineering may be simply a call for some parallel movement in the surface ship domain.

CHAPTER 4

REINVENTING SHIP CONTROL STRUCTURE

Each chapter of this report reflects the premise that future Navy ships should be designed from a total ship perspective to serve as elements of a capable and jointly interoperable Navy warfighting system. Chapter 1 notes that total ship engineering begins with the idea that a warship must act as a coherent warfighting system, all parts working in unison to maximize operational effectiveness. From hull form to launchers and missiles, every part of the ship must contribute to the overall goal of ordnance on target. Chapter 2 argues that future designs must weave combat, support, hull, and machinery modules into a system of systems configuration with a mix of firepower, stealth, survivability, and affordability characteristics that meets all operational requirements. This demands efforts to establish a comprehensive system engineering framework for ships. Chapter 3 provides a domain reference model for surface ships, indicating that control structure drives the ship's ability to act as a coherent entity. This chapter considers what the control structure of a surface ship should be, from a top-down perspective.

POINT OF DEPARTURE

The strategy for partitioning control resources on a total ship basis is rooted in basic principles of system engineering. The first principle to be considered is that the aim of design must be to help the warfighters in achieving their operational objectives. The mission teams carried to an operating area, where they may be called upon to maintain presence or to deliver high-tech firepower against an adversary, must be the primary concern. The principal outcome desired in total ship system engineering is to build ships that will (a) meet the needs of the on-board mission teams and (b) enable on-board teams to contribute effectively to other mission teams within the battle organization established by a theater level commander.

In future conflicts, these teams will face multiwarfare threats in difficult operational environments, and expeditionary operations with joint, allied, and coalition forces will be emphasized. Beyond this, as Figure 9 suggests, ship roles and tasks are characterized more by uncertainty than any other single feature. To support mission teams under these circumstances, ships must be flexible, capable of tailoring basic capabilities to a designated set of mission tasks and operating environments. They must also be able to operate as an integral part of joint or coalition expeditionary forces.

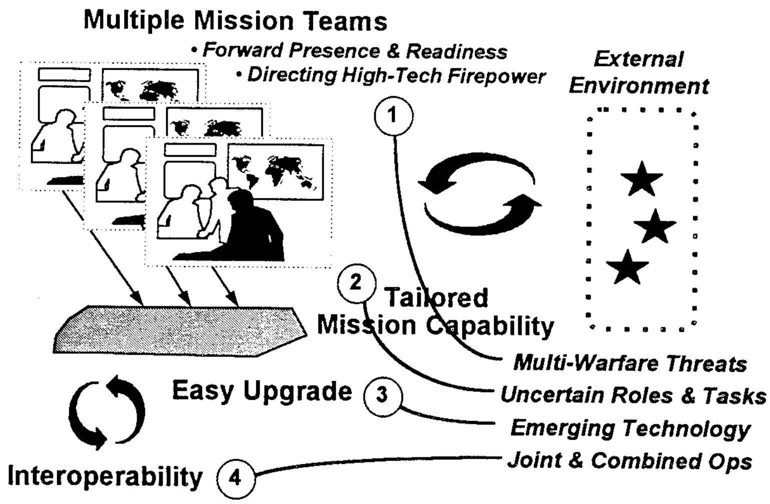

FIGURE 9. WHAT FUTURE SHIPS MUST DO

Given the rapid pace of technical progress, the ongoing "revolution in military affairs," and the importance of affordability, use of open system designs must also be emphasized.

A second key principle of system engineering is that systems should be partitioned so that the major subsystems created are loosely coupled (weakly interacting). The approach is therefore based on considerations of domain clarity and distinctiveness, stability of domains and associated interfaces, and minimal crossover (i.e., each module should interact weakly with other modules). The importance of this last property is that where it applies a designer can change one part of a system without creating a cascade of compensatory changes to other parts. When the internal state of one module has a strong bearing on the internal state of other modules, decomposition could complicate rather than simplify the design problem.

Following the principles cited, the question of partitioning for total ship command and control is considered below from a warfighter's point of view. Regardless of the approach to spatial arrangement and physical modularity, a control structure is necessary to make ships responsive to command direction and control. In defining a framework for design of control structures on a total ship basis, we start with the simple view of warships shown in Figure 10. This view shows people at the top, mission resources at the bottom, and control interfaces (or command and control interfaces) in between. The control interfaces provide a backbone structure that links mission teams with the resources necessary to perform assigned tasks and make the mission resources responsive to human direction and control.

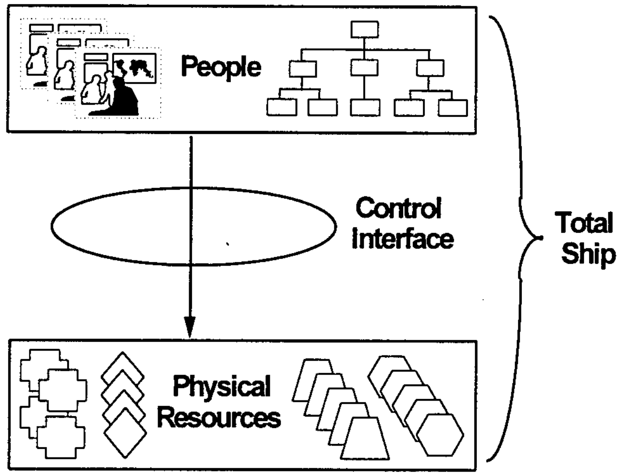

FIGURE 10. POINT OF DEPARTURE FOR
TOTAL SHIP ENGINEERING

At one time, resources were under direct control of the warfighters. Training a gun or changing a fuel flow rate meant repositioning a lever or valve. Today, computing systems are widely used for control functions. While the number of people involved is somewhat less, what warfighters must do remains the focus of attention. Only under direction of its mission teams does a ship become a complete warfighting system, a combatant, capable of acting on its own to achieve a designated military purpose. Even a fully automated ship would execute broad plans and orders from a human commander.

PARTITIONING OF CONTROL LAYER

From a warfighting point of view, the first concern is the military purpose of the ship and its intended operational use. For surface combatants, this means putting ordnance on target. For amphibious and auxiliary types, it may involve (among others) sealift, amphibious assault, mine countermeasures, or command support operations. In any case, command elements must govern the operation of mission-critical systems and their interactions so that the ship can accomplish its fundamental military purpose with efficiency and dispatch. A second important concern is posturing the ship for operations through readiness assessment and resource management. In a broad sense, what is involved here is to provide for integrated command and control of own ship mission operations, readiness posture, and information flows. An expanded view of this structure, regarded as a top-level partitioning for overall control responsibilities, is shown by Figure 11. Rationale for this partitioning is considered below. The structure

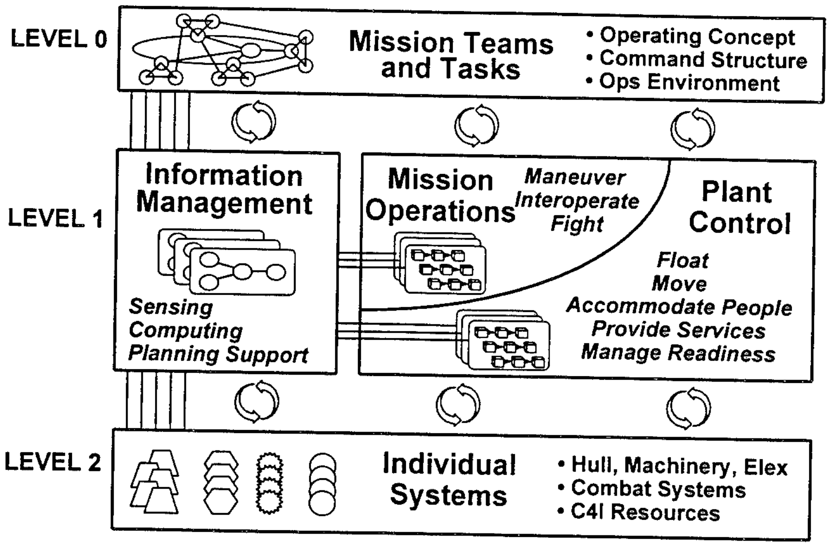

FIGURE 11. LAYERED CONCEPT FOR TOTAL SHIP SYSTEM OF SYSTEMS

shown is quite general in nature, and use of the term "mission operations" makes application to amphibious and auxiliary ship types a fairly simple variation. However, the final test must be whether it captures what is most important to command. A number of experienced commanders and trainers should be consulted to ensure the chosen structure is consistent with Navy doctrine and operationally effective.

Uncertainty is the central factor with which all command and control systems must deal, and a major factor in selecting an appropriate control structure. In general, the more important the human element in a given situation, as opposed to the technical, and the more important enemy actions are in shaping that situation, the greater the uncertainty involved. Ship containment, mobility, and support systems thus tend to be organized by function and controlled in a top-down fashion, and the chief concern is to keep essential operating and support systems ready to act when needed.

The chief concern in combat operations is to carry out essential mission tasks: maneuvering, fighting, and cooperative interaction with other units. The combat resources are thus organized by mission area and every effort is made to preserve freedom of action at the bottom of the command structure. Combat operations tend to call for more intensive use of information, and may demand a greater share of command attention than tasks associated with ship systems. Thus, different organizing principles are appropriate in the two domains, and they generally have separate work units in ship command structures. Indeed, relatively little attention has so far been given to automated means for integrating ship command functions across the two domains. Today, it is widely recognized that the boundary lines between them are shifting; maneuver control and damage control coordination are increasingly important concerns that may move across this boundary.

A third domain, information coordination, allows command to interact purposefully with on-board or off-board correspondents. In addition, it accommodates changes in command and control structure by reconfiguring information flow paths. Confronted with a task, and having less information than is needed to perform that task, an organization may react in either of two ways. One is to redesign the work process (and organization) in such a way as to permit effective action with less information. The alternative is to increase the information processing capacity. Both methods produce changes in system information flows. This may involve changes in decisions and reports, in terms of what decisions and reports are made or in terms of who makes them. It can also mean changes in task organization and internal communication patterns, or reallocation of resources to get essential information through new sources and methods.

A separate work unit is needed for information coordination because it involves a service that supports both of the other domains. The way we design and build today's surface combatants reflects a hidden assumption that information and control flows are relatively static. We may expect the data in these flow paths to change as orders are received, the tactical situation evolves, and ordnance is expended; but we do not expect or provide for redefining the way system tasks are performed and coordinated. But configuration changes may be needed for a variety of reasons. Reconstitution or upgrade, use of services from systems on other platforms, and evolution of design baselines mean changes that can redefine system characteristics over a long time line. Shifts in operational modes and threats, battle damage, equipment failures, and the desire to tailor operating modes to specific operating environments may call for corresponding changes to a ship's patterns of information flow.

With modern designs, however, the assignment of resources to a given action path need not be a fixed characteristic of the design. Resource assignments may be dynamic, varying with assigned missions and tasks at any point in time. Design of system elements for any-to-any interconnection can support a virtually unlimited repertory of subsystem and segment configurations, with flexibility to create new operating modes tailored to specific operating tasks and roles. A large repertory of configurations and capability profiles can enhance a commander's ability to achieve surprise in tactical operations and thus dictate the terms of action. Reconfigurable data and control paths also create opportunities for increased survivability and growth potential compared to fixed path designs. Creation of a separate information coordination backbone (as discussed in the next section) can make future surface combatants better able to continuously redefine information and control flows by altering interconnection structures.

BACKBONE ROLES AND CHARACTERISTICS

How the control structure is formed plays an important role in defining and controlling the development of a warship as a system of systems. Just as the domain model of Chapter 3 permits a common understanding of goals and requirements at the level of individual systems, consideration of backbone roles and characteristics promotes a common understanding of how control functions and interfaces should be handled. An expanded view of features envisioned for the mission operations, plant control, and information flow control backbones is thus given below.

Mission Operations. A ship's battle organization typically contains several mission teams, each capable of performing some essential mission task. The mission operations backbone must provide a common framework linking these warfighting teams to ship resources and supporting the use of those resources to achieve the ship's fundamental military purpose. This backbone provides the control structure necessary to fight the ship as a unified and robust operating entity and must enable the command team to integrate all aspects of target processing with tactical maneuvers, cooperative interactions with other units, and damage control coordination as necessary for effective mission operations. Key internal considerations include how the ship will be organized for maximum effectiveness across its key mission roles and tasks. This involves battle organization, mission planning, and tactical maneuvering capabilities. Key external considerations include how the ship is organized to deal with external partners, clients, and competitors. In particular, the overall command structure for naval forces in the theater of operations must be considered.

However, the mission operations backbone would differ in several ways from today's combat systems. It is intended to control all aspects of actual warfighting, to include such tasks as tactical maneuvering and damage control coordination, long considered elements of HM&E. Training and readiness management tasks, which are assigned elsewhere, may be replaced by such tasks as control of operations by embarked vehicles, likely to involve surveillance and fire control support. The result will be a system of systems that includes most combat capabilities, but with changes appropriate to contemporary notions of combat operations. In contrast with today's systems, however, it is envisioned that the warfare mission areas will employ a common operating environment, limiting the use of noncommon features to mission-specific applications.

Readiness and Plant Control. The readiness and plant control backbone is intended as a common framework for transforming the ship's physical resources into ready capabilities for use by warfighting teams in achieving mission objectives. This backbone must provide for continuous availability of essential warfighting capabilities even if system failures occur or battle damage is present. Design emphasis must be given to features enabling the crew to operate and maintain tactical systems at design performance levels despite the harsh physical environments, imperfect logistics, and fallibility of both human and machine systems that must be expected in joint and expeditionary warfare operations. Key internal considerations include organization and optimization of resources within and across functional areas, and optimizing relationships between functions. Key external considerations include logistic support planning and access to remote services, such as test and maintenance assistance.

Information Flows. A third backbone is needed to set up and coordinate information flow paths within the ship. The chief concern is to allow individual systems to interact purposefully with on-board or off-board elements or systems. The intent is to create a utility that coordinates information flows throughout the ship, but leaves actual use of the resources provided to individual mission teams. This includes coordination of the mission-oriented flows necessary for combat operations; the function-oriented flows necessary for plant control; and any summary information necessary for command. It also provides for coordinated use of the inherently shareable information provided by communications, computing, and sensing systems. Technology will permit dynamic reconfiguration of information flow paths in future warships, and mission requirements will dictate that this potential flexibility be exploited. The potential for a doctrine-driven approach is significant.

An important feature of information systems is that service attributes are a driving factor in system organization. Surface combatants have many subsystems, with various elements exchanging data to achieve coordinated action. The subsystems will differ in attributes such as time criticality, system integrity, modes of communication, security, certification, granularity, and perishability of data. It can be expected that information flow paths will be divided into several segments to keep within the capacity of standard networks (including design margins to allow for latency requirements and system expansion). Elements with similar attributes will be placed in the same segment where possible, and intersegment flows will be minimized. In short, information flow paths ought to be organized by service attributes, rather than mission tasks or functions as in the mission operations and plant control domains.

The maturation of distributed computing technology may be the occasion for significant improvements in configuration flexibility. Distributed computing typically demands a high level of configuration management capability because of the frequency of field reconfiguration and upgrade actions. Configuration management tools are used to define node addresses and relationships between nodes, add new nodes and replace any which are defective or obsolete, and test nodes or functions necessary to properly start up and maintain systems and processes. These configuration management requirements tend to come as a surprise to many people moving from centralized to distributed computing architectures; earlier systems never had to replace or even to address nodes. Relationships between nodes were determined by algorithms programmed into the central control unit. Change meant costly modifications to system wiring and access to system integration expertise. But the "necessary evil" of system management is really an enabling tool to harness the new potential of distributed systems for improved configuration flexibility and ease of maintenance.

One application of this new potential is to make embedded control capabilities more reliable. Recent decades have seen a trend to decentralized control structures with static interconnection patterns that are quite vulnerable to control node failures. The term "decentralized" refers in this context to the control information pattern. It signifies that within a given layer of the control structure different nodes have access to different (specialized) information. For example, an antiair warfare coordinator would not have access to strike data. From the reliability point of view, this approach relies on series connection of nodes, yielding no redundancy in control capability.

A key principle of system engineering for complex systems is that unreliability of components should be overcome by organizing them in such a way that the reliability of the whole is greater than the reliability of its parts. This is an idea formulated in design of reliable computing systems and extended to control structures only recently. Parallel (or multiplex) designs can be achieved in control structures by using multiple control nodes. The key is to provide for multiple interconnection paths so that when one controller fails the other is capable of carrying on the plant. The failed node can then be disconnected, tested, and repaired or replaced without interrupting system operation. With the flexibility afforded by network technology, it becomes possible for ships to continuously redefine control structures by activating new paths of information flow.

STRUCTURAL FLEXIBILITY

Shipboard command and control tasks involve at least two levels of integration. One is the overall command level. Major design concerns at this level include basic organization of the command team, integration of mission teams across different physical locations, and interoperation (collaborative work) with other commands. The second level is that of mission teams, in which several individuals perform a related set of tasks. In general, task teams are formed by one of the following methods:

- Area (by grouping together all forces within a geographic area from whatever service or nation or for whatever purpose)
- Service or nation (by grouping in each subdivision all forces from only one service or nation)
- Medium (by grouping together all ground forces, air forces, and seaborne forces from whatever nation or service)
- Task (that is, grouping together all forces directly involved in accomplishing the same task from whatever service or nation)

Some organizational structures reflect a mix of these options. In the recent past, open ocean task force operations were seen as the primary role of naval forces. Surface combatants were organized by warfare mission area to support the Navy's composite warfare command concept for war at sea. Task and medium were closely aligned as the basis for this approach, and surface ships organized for battle by warfare mission area teams. In the future, surface ships may serve as elements of naval expeditionary forces, joint or combined forces, or interagency task forces (as in peacekeeping operations). Each of these force types could employ a different command structure and place a different set of demands on the ships involved. The key question is whether some command structure will be generally useful for naval forces, across all three force organizations, or whether a variety of different command structures will be needed. In either case, warships will probably mirror the preferred force command structure.

Littoral warfare operations seem likely to demand increased flexibility in surface ship command structures. Dealing with the littoral warfare environment could make it necessary to alter how naval forces and ships are organized to deal with their external partners, competitors, and stakeholders. Warfighting and force employment strategies, force composition, command structure, threat, and operating environments may vary greatly in future conflicts. In this era of uncertainty and change, the battle organization may need to change to meet specific mission needs, make best use of available personnel, or exploit a particular tactical situation. Two things must be done to meet this challenge. The first is to identify system engineering methods that allow a satisfactory design to be created and that can be used to choose between design alternatives. This will become part of the foundation for managing overall system life cycle cost and integrity. The second is to identify a design that will support a large measure of operational flexibility.

While "big change" may play out only over many years, the importance of flexibility can be highlighted by scenarios for change. One scenario calls for a command team structured to deal with power projection, battle space dominance, C^2S-information warfare, survivability, and mobility as the major operational tasks to be performed. The important consideration for this discussion is that the creation of any new mission structure requires a corresponding realignment of the battle organization. A variety of special purpose teams may also have to be supported. For example, this could include formation of a joint air identification team; integration of a US Marine Corps air defense control team, using embarked rather than organic facilities, into the ship's combat control structure; and embarkation of a Force AAW Commander and staff. Other examples are easily added to the list. Indeed, each forward deployment cycle might call for a different command structure or variation from some core structure. It could also be necessary to adapt to changes in the structure of joint commands *as a conflict situation evolves*. A design that makes physical rearrangement of warfighting teams and work stations easy is then important. Decision aids (such as templates) for tailoring a ship's command structure to specific mission needs represent a second step forward in flexibility.

An open systems approach facilitates change. The initial design should be viewed as the nucleus of a more advanced or larger system, with hooks installed to support change scenarios. Direct and dedicated support should be provided for a range of alternative battle organizations, action options, information flow patterns, and tactical procedures, tailoring ship capabilities to the designated mission and operating environment. Force command roles depend on the ship's capabilities for external communications, tactical picture formation, and configuration to support command and control systems and structures of expeditionary, interagency, joint, and allied forces.

Such operations demand the ability to make ship resources available to a shifting array of coalition partners and tasks. Heavy demands may be placed on airmanship, seamanship, and emergency assistance skills as well as ready mission capabilities. Mission capabilities must include a large repertory of options for flexible and reliable performance of engagement, peacekeeping, tactical maneuvering, and interoperation tasks. It is essential to accommodate a wide variety of operational, physical, and threat environments.

TOWARD A SHIPWIDE CONTROL ARCHITECTURE

The open systems paradigm can be applied to surface ships as shown by Figure 12. The diagram is a variation of the basic entity-relationship model used in Reference 29 to define the NIST Application Portability Profile and again in Reference 30 to define a technical reference model for DoD information systems. The ship is viewed as a layered open system with three entity types and two interface types. The target architecture represents a strategy for applying the concept of open systems to warship development. The aim is combine the qualities of portability and interoperability sought in open systems design with the effectiveness and reliability sought in surface combatants.

The target architecture is layered to form two loosely coupled subsystems. The first links application software entities to application platform entities. As in the NIST Profile the basic idea is to make the services provided by the application platforms (at their interfaces) transparent to application software. This first subsystem is then loosely coupled, in that application platform entities are interchangeable and application software entities become reusable.

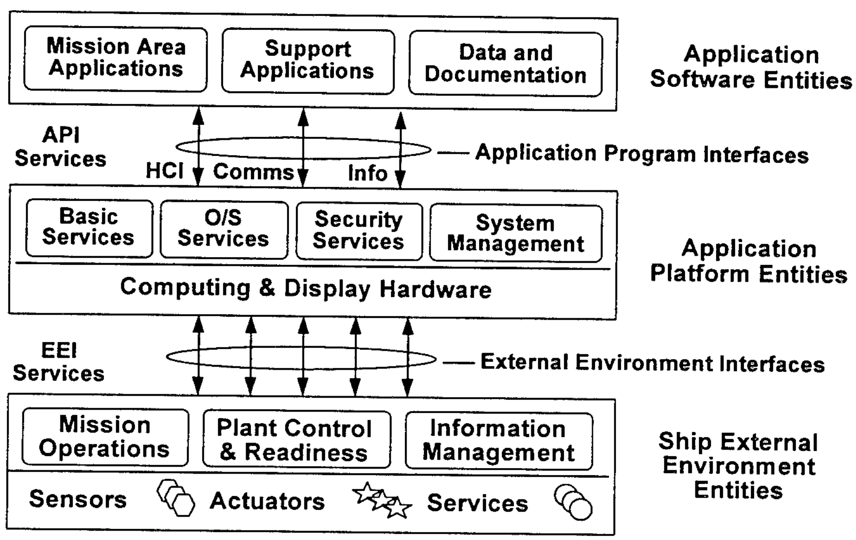

FIGURE 12. TOTAL SHIP TARGET ARCHITECTURE

The second subsystem links external environment entities to application platform entities. Again, the basic idea is to make services provided by the latter (at their interfaces) transparent to individual sensors, weapons, work stations, machinery, and service systems throughout the ship. Both application platform entities and external environment entities are viewed as providers of standard services, and any two elements providing equivalent services should be interchangeable.

As indicated in Figure 13, the benefits of a common backbone are applicable to all three backbone areas (mission operations, plant control and readiness, and information management). What is envisioned is a generic backbone (with variants tailored to each area) that supports design for modularity, commonality, and the sharing of functional resources on a shipwide basis. The generic backbone would provide the following characteristics:

- Command spaces become utilities, tailorable to any set of mission teams and tasks that may be operationally required.
- Computing, communication, and display resources are managed on a shipwide basis, with a common application environment maintained.
- Resources and readiness characteristics are managed on a shipwide basis.
- Life cycle costs are reduced through efforts to hold manning and parts count to minimum levels and adopting an open systems approach.

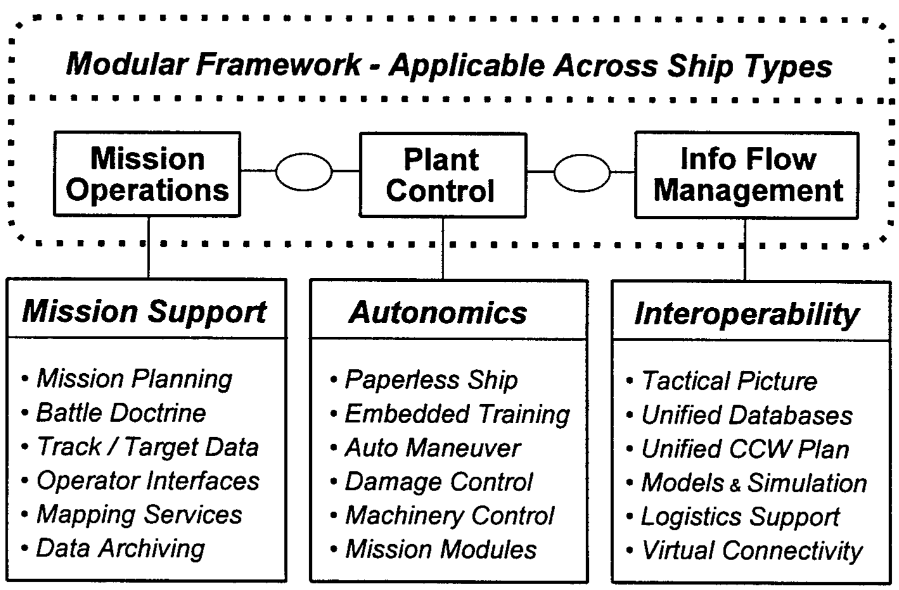

FIGURE 13. VISION FOR TOTAL SHIP INTEGRATION

Capabilities sought in the individual areas are identified in the bottom part of Figure 13. Overall, the resulting architecture is intended to be enduring, flexible, permitting application to a variety of ship types and designs, easy insertion of new functionality as warfighting systems evolve, and insertion of new technology as it becomes available. The original backbone architecture should include an extension framework and be subject to formal change control from the earliest stages of development. Many of the capabilities envisioned for plant control and information management are described in References 20, 39, and 40.

Based on the total ship engineering process and partitioning scheme outlined above, reengineering opportunities have been addressed for the area of mission operations. The main question considered in this effort was whether it makes sense to talk about a common system engineering framework across many different projects in the combat system area, as suggested by Figure 14.*

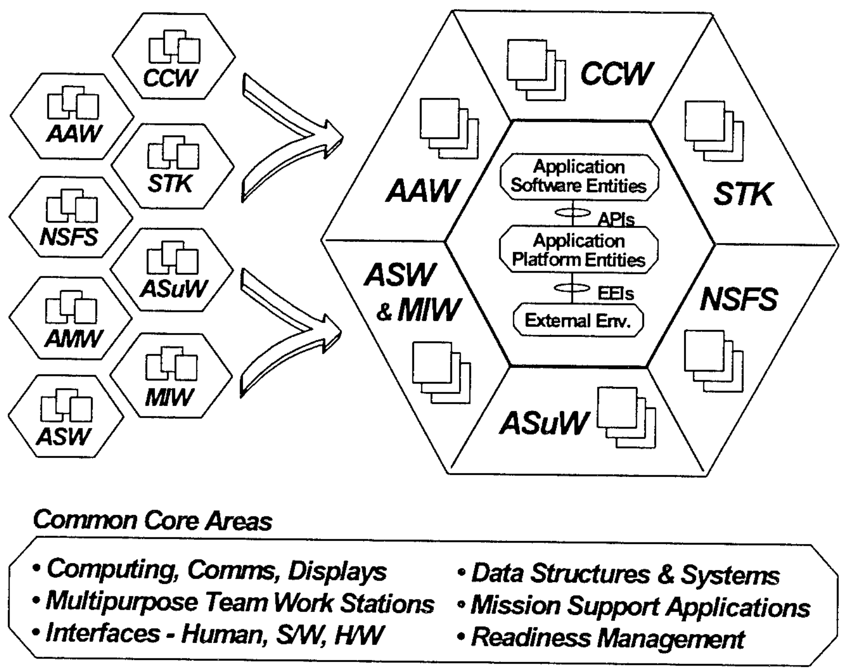

FIGURE 14. VISION FOR COMBAT SYSTEMS

Results indicate a common backbone structure may be feasible in future combat systems. This would mean, for the combat system as a whole, the kind of flexibility and resource sharing achieved by the Mk 41 VLS in handling multiple missile types, or by the AEGIS Weapon System in handling multiple, simultaneous targets. The idea of a

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*Warfare areas shown are AAW, antiair; NSFS, naval surface fire support; AMW, amphibious; ASW, antisubmarine; CCW, command and control; STK, strike; ASuW, antisurface; MIW, mine.

common operating environment (COE)* is usually applied only to a computing environment. Creating a common backbone for mission operations (combat control) means a COE defined more broadly, to include not only computer resources but also watch stations, interfaces, communications, displays, and mission support applications. Common system services should also be provided to deal with configuration management functions (such as naming, or providing a common data element dictionary). The backbone would provide a standards-based framework for development and integration of individual combat systems. The individual system programs would then be able to focus on delivery of mission-unique applications and components. Use of an open system framework can make this both affordable and capable. The potential benefits appear very significant.

ALTERNATIVE PARTITIONING STRATEGIES

While the concept shown in Figure 11 has been considered carefully, it is important to note that any partitioning corresponds to a particular view of the system. Since many viewpoints can be appropriate, or even necessary given different aims, it is believed that alternative partitioning approaches should be considered and discussed. Partitioning strategies differ in the dimensions considered and the importance assigned to them. Space and time, mission, function, and service attributes are among the dimensions most often considered. One alternative is the work breakdown (department) structure used in today's ships. This leads to partition elements such as navigation, operations, engineering, combat, supply, medical, and administration. A second alternative is formed by breaking the traditional HM&E systems category into ship services and mobility. The partition elements are then combat, services, and mobility. Since information services can be treated as only one among many services, this approach may be workable. After long dialog, debates about partitioning tend to turn into naming contests, with little substantive difference among the leading contenders. For example, several dozen paradigms can be identified for command and control. The alternative paradigms are considered by Reference 41, which notes that most offer little in the way of new problem insight.

In time, major changes are likely in how military forces are organized to use information. This could mean evolution of collaborative work styles, based on the use of team work stations designed around advanced displays. Instead of hierarchies, in which bottlenecking limits flexibility, future systems may use network structures extending across the ship's life lines. For example, use of a wide area net to provide fire support to ground forces ashore is easily envisioned. A third key source of change

* *Common Operating Environment* - A ship may be viewed as a distributed system with a large array of components, including people and information resources as well as equipment items. What turns this array of components into a system is an infrastructure that provides facilities for resource management, interconnection, and control across components. Use of a single infrastructure, extending across all mission areas and functions, would result in a common operating environment for the ship. In contrast, today's ships generally have different (and noncompatible) infrastructures in each mission area.

in work units is automation, which can alter task allocation between humans and machines and create change in basic work processes as well. To prepare the way for change, it is important to establish a disciplined process for managing control flexibility and integrity on a total ship basis.

CHAPTER 5

IMPLICATIONS FOR DEVELOPMENT

The purpose of this chapter is to summarize implications of the overall report for definition of a total ship system engineering process. This has been done from the viewpoint of the development organization responsible for ship design, acquisition, construction, and support. The chief concern of this activity must be to ensure that all major design decisions are based on what's best for the Navy as a whole, rather than what's best for any particular component or class of systems. This makes total ship system engineering as much a process control or coordination problem as it is a technical problem.

ENTERPRISE CONCEPT

Despite the many twists and turns in acquisition policy, the core process of ship system engineering appears to have been fairly stable over time. The core process bears some resemblance to the command and control approach pioneered by the General Motors Corporation circa 1930. Figure 15 outlines the main characteristics of this approach whose overall strategy is to centralize planning and decentralize execution. As practiced by industry, the process emphasizes vertical integration for in-house execution. Up to 70 percent of total value may be produced by in-house activities,

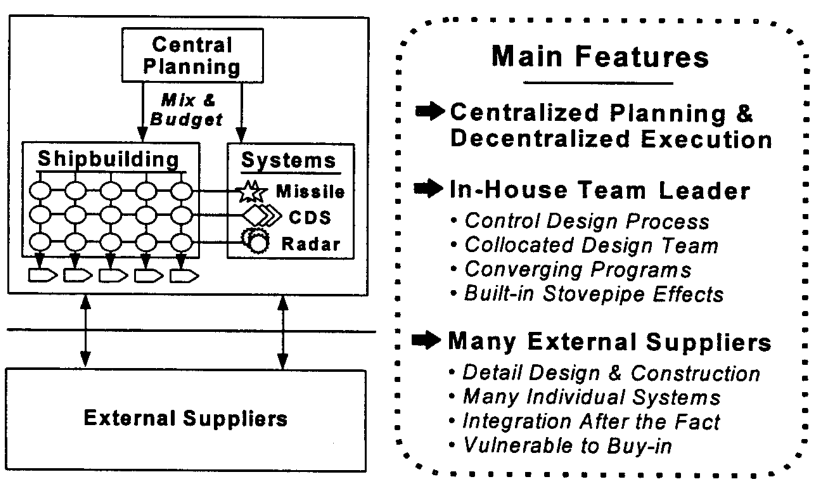

FIGURE 15. UNDERLYING CONCEPT OF SHIP ACQUISITION PROCESS

and the remaining 30 percent typically includes bulk materials and commodities that are widely available. A central engineering staff designs components and gives detailed drawings to the suppliers for bid. Bureaucracy drives relationships among the in-house activities, while price is the principal factor in dealing with external suppliers. The acquisition process can be quite vulnerable to buy-in.

The Office of the Chief of Naval Operations (OPNAV) provides the central planning for Navy ships, while NAVSEA executes the programs. Ships are designed by a central engineering staff, with construction by a privately owned shipyard. Many ship types are produced, each with different mission-critical systems but many common components as well. A typical ship has thousands of functionally complete components and scores of individual systems, each designed for a specific purpose. Scores of acquisition programs and thousands of suppliers are involved in creating the components and delivering them to the shipyard. The scope and complexity of the enterprise* tends to limit use of common designs across the entire Fleet.

The future development organization should be structured to maximize value delivered to mission teams on a life cycle basis. While no specific form of organization can yet be recommended, Figure 16 indicates the broad pattern envisioned. In fact, industry has turned reinventing the enterprise into something of a global trend. For the most successful efforts, thinking in terms of a value stream has been the crucial first step. This drives the role of the enterprise leader, who must act to shape the overall value stream and not the value added by direct effort alone. This causes a shift away from stovepipe thinking to global or team thinking. In particular, greater attention

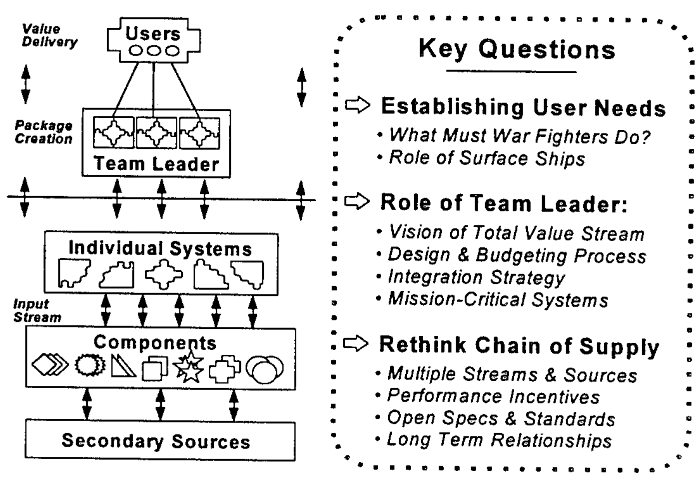

FIGURE 16. ORGANIZING FOR VALUE STREAM INTEGRATION

* An enterprise is defined as not a single activity but a group of activities working together to supply a good or service in a way that creates maximum value for the customer.

is given to relationships among team members, and to the transactions between them, which often have the most potential for effectiveness and productivity gains. The figure indicates how such an enterprise might be structured. It has three layers, corresponding to value delivery, product assembly, and component input activities.

This approach is widely viewed as an improved model for design of large productive systems. The original implementation is credited to Eiji Toyoda and Taiichi Ohno and sometimes called the Toyota Production System. The basic aim was to form a vast group of suppliers and parts plants into one "machine" by producing at each step only those parts necessary to satisfy immediate demand at the next step. The final assembly organization functions as enterprise leader. Usually, design and production of components that tend to define product style and performance are supplied in house. Thus the enterprise maintains control of the product line, but external suppliers provide as much as 70 percent of total value added, while in-house activities generate only 30 percent.

Suppliers are organized into functional tiers, with multiple products and multiple sources in each tier. First-tier suppliers have an integral role in product development and are assigned a whole component to design. The suppliers work to a performance specification for a system which must work in harmony with other components, from other suppliers. Toyota formed first-tier companies by spinning off in-house divisions and building long-term alliances with external suppliers. Production is typically shared among several sources, with shares fluctuating up or down according to performance.

Second-tier suppliers tend to specialize in a manufacturing process. A first-tier supplier might design an alternator, for example, and buy all parts from second-tier suppliers. The latter have no role in overall product design but may produce drawings for individual parts and have firms at still lower tiers produce parts to those drawings. Since companies at this level normally do not compete for specific component types, they can work together in supplier associations for the purpose of sharing information on manufacturing techniques.

The concept of operation is based on mutually agreed pricing, strong incentives for performance and sharing of information, and long-term relationships. Direct competition for production work between in-house and external activities is avoided, as it tends to be inefficient and unfair.

Ships are a capital good, so the organizational model from industry has meaning for ship design, acquisition, and construction. The basis for organization is then to maximize value delivered to mission teams on a life cycle basis. The enterprise leader is viewed as an integrated program team with both Navy and builder elements. In essence, the lead activity controls the overall design process, including weight, space and cost budgets; the strategy for integration and control of mission capabilities; and creation of the mission-critical systems which are the reason for taking the ship to sea. Beyond this, it would be useful to rethink the entire chain of supply, seeking to adopt the best practices from major enterprises around the world. At each tier, supplier associations may be formed to create and to promote the use of open specifications and standards. Process improvement techniques can also be shared. First-tier suppliers (major systems) should participate in overall ship design. Lower-tier suppliers may be encouraged to participate in both commercial and defense markets. Ideally Navy R&D results would be shared among same-tier activities.

PROCESS MODEL FOR SHIP DESIGN, ACQUISITION, AND CONSTRUCTION

Figure 17 shows a process reference model for the development team leader. It has been organized into five layers, with each layer responsible for a defined set of system engineering services. A similar model for software development in large-scale systems is considered in Reference 42. The model encompasses the entire set of activities required to create and evolve warships. The model framework consists of a set of layered services. The framework is flexible and reusable, as individual services can be added, modified, or deleted from each layer. The purpose of the reference model is not to make an already complex problem worse, but to clarify, structure, and rationalize the complexity inherent in the problem. Systematically defining these services as organizational layers exposes the requirements and responsibilities for their definition. The model is thus a step toward the establishment of a common framework for total ship system engineering.

Layer	Descriptor	Services Provided
0	Framework	Services used in defining and maintaining the total ship system engineering process
1	Main Characteristics	Defines main characteristics for the ship as a system of systems
2	Coordination	Coordinates system engineering activity across many individual systems
3	Individual Systems	Defines the system engineering process for individual projects
4	Individual Products	Describes individual work products created for the individual systems

FIGURE 17. LAYERED PROCESS REFERENCE MODEL

Framework

The function of Layer 0 in the reference model is to provide services used in defining and maintaining the process of interest. As indicated above, forming a process definition team is recommended as the starting point for creation of a total ship system engineering process. The system engineering process maturity model, Figure 18 and Reference 43, offers some guidelines for process definition and management. As a look at the figure will show, recognizing that a system engineering process achieves maturity in stages is an important feature of the guidelines. Adopting formal methods of process definition and management is a step forward from the ad hoc methods normally employed. Chapter 2 noted the chief attributes sought in the process: teamwork, a system of systems engineering approach, and reliance on shared concepts, standards, and tools to promote design integration.

5 - Optimizing	**Continuous Process Improvement** *Focus on Feedback*	System Problem Prevention Technological Innovation Process Management
4 - Managed	**Quantitative** *Process Data Base*	Process Measurement Problem ID & Analysis Quantitative Quality Plans
3 - Defined	**Qualitative - Defined & Institutionalized** *Process Improvement Group Established*	Standards and Training Reviews and Testing Inter-Discipline Coordination LC Balanced Product Eng. Integrated Systems Mgt.
2 - Repeatable	**Intuitive - Process Depends on Individuals** *Focus on Project Management*	Requirements Management Project Planning & Tracking Configuration Management Quality Assurance Risk Management
1 - Initial	**Ad Hoc /Unpredictable**	

FIGURE 18. SYSTEM ENGINEERING PROCESS MATURITY MODEL

Teamwork. The first and most important step is probably to form a cadre that is able to consider tradeoffs from a total ship perspective. This calls for a broader perspective than usual, but one with a full appreciation for, and easy access to, the specialized technical knowledge of functional activities and the warfighting community. In particular, some way must be found to foster and control dialog between the different engineering disciplines involved. A team effort is very difficult because the problem is very complex. Adoption of a common language and pursuit of a sustained dialog on problems and opportunities in the domain can help a cadre learn to communicate well enough to permit good teamwork.

Once a coherent framework is established for solving key problems over time, individuals may be able to work effectively together from different locations, as long as frequent communication is encouraged. To begin, a training standard for the cadre should be created by defining an agreed-upon baseline process.

System of Systems Framework. This refers to the approach of Chapter 2. Early in the process of cadre building, formation of a strategy team should also be considered. Such a team can help articulate a domain model (Chapter 3), creating a shared conceptual framework and vocabulary to promote cadre formation. The first attempts to define new programs involve much risk, and expert advisors (who have run the course successfully) can help with initial plans and strategies. In early plans it may be necessary to anticipate decisions yet unmade, or contingencies yet to arise. Because a ship is only a component of some larger system, many threads must be woven together to formulate an overall program strategy.

Information Sharing. As suggested by Figure 19, computer networks can facilitate sharing of information across different work sites. Today it is possible to think of a team being brought together on the network, sharing data and holding meetings entirely via the network using common design aids and groupware. A virtual team is an integrated

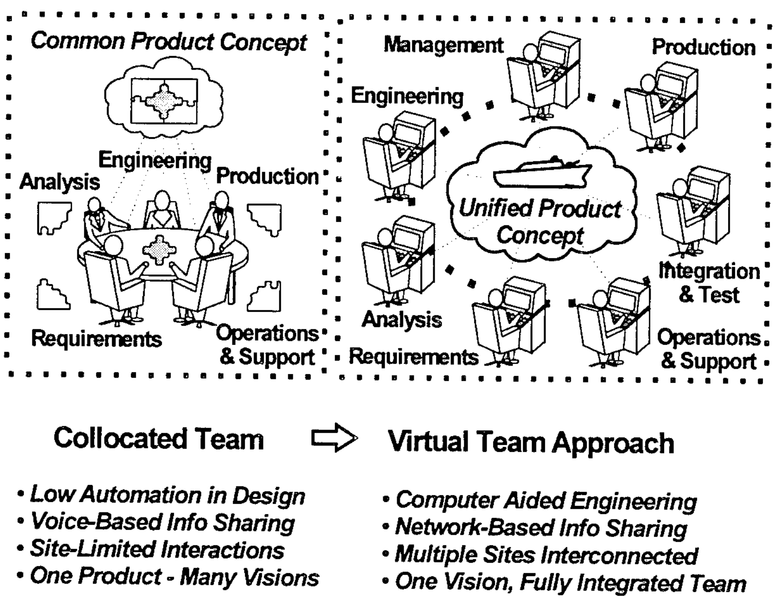

FIGURE 19. TEAM WORK ENVIRONMENT

product team with members using powerful computer-aided design (CAD) tools in their individual workspaces but publishing results to a shared information base. A coordination service may exist to schedule work, report progress, notify persons, authorize work, and coordinate execution of work processes without the need for face-to-face meetings.

Main Characteristics

The function of Layer 1 in the reference model is to define the main characteristics of a total ship system engineering process using Layer 0 services. A key principle of system engineering is that the work units should be organized around the loosely coupled subsystems formed by partitioning. The implication is that a partitioning for total ship design must be driven first and foremost by operational considerations, and the development team structured accordingly, rather than the other way around. Those activities shown in Figure 20 are seen as core concerns of the development team leader. They parallel the ship control structure shown in Figure 11.

Because it must deal with acquisition and integration of individual systems as well as overall ship construction, team structure is a bit more complicated than the operational control structure. Once a basic understanding of mission teams and tasks

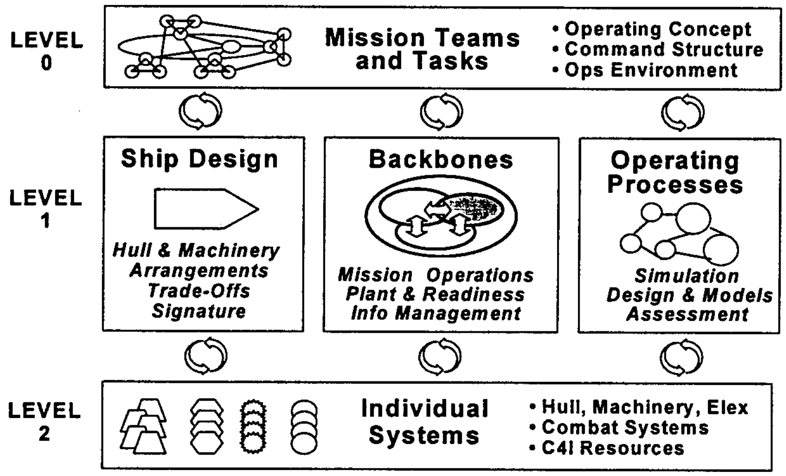

FIGURE 20. LAYERED CONCEPT FOR TOTAL SHIP DEVELOPMENT

has been established, the development team must address overall ship design, the definition of backbone control structures, and the definition of specific operating processes, adequate to meet all mission needs. Each makes a key contribution to creation of a total ship system of systems from the host of individual systems which will be delivered to the shipyard. If the development team leader activity has direct control of development for specific mission-critical systems (i.e., new capabilities central to the ship's military purpose), they may fall into this category as well.

Mission Teams and Tasks. The first step toward defining a ship must be to consider how warfighters envision its use. This is possible only if experienced operators can be directly involved in the creation and review of technical planning efforts. Thus mission teams and tasks should be taken as the starting point for total ship system engineering. Primary emphasis is on understanding what future mission teams must do, what corresponding warfare processes will be like, and what information will be needed to execute those processes. Success has been achieved only if (a) an executable system design description exists and (b) acceptance criteria for the ship have been nailed down. These criteria reflect how the user will see the ship and key mission systems (and interact with them) as the tasks laid out by the concept of operations are performed. This may include tactical and technical experiments to develop or refine system concepts.

It is important to ensure an effective and open process for requirements consideration. The Mission Needs Statement (MNS) provides a baseline for understanding operational requirements, but it will be necessary to repeatedly refine, clarify, and extend this baseline as development activities proceed. The system engineering process must provide for transformation of key operational requirements into system technical requirements, traceability of design features to intermediate and top-level requirements, and management of requirements information. The integrity of the system engineering process depends on the handling of requirements: it's "garbage in, garbage out." Any problems should be explored and resolved through dialog with OPNAV and Fleet points of contact. Based on structure and content of the requirements data, a preliminary functional description should then be constructed for each major mission and for each backbone area. This breakdown should include no more than three levels of detail; i.e., Tiers 0, 1, and 2. Where possible, measures of performance traceable to requirements should be identified for each function.

Ship Design. This activity provides the design studies necessary to address the questions of ship form, size, and essential military characteristics. Speed, seakeeping, strength, stability, and style are the major naval architecture issues. These characteristics are all interrelated and dependent on overall ship configuration and dimensions. Accordingly, the design activity has an important role in establishing configuration baselines for the ship and controls the general arrangement to achieve spatial and mass balance. Thus it controls the design budgeting process for the ship, possibly including signature and survivability as well as the usual weight, space, moment, and cost factors. The design activity also has an important role in providing the physical interfaces (spatial, mechanical, and electrical) necessary for the many individual systems packaged into a multimission ship. Virtually all the resulting information finds its way into the drawings and specifications used to select and provide technical direction to a shipbuilder.

The overall task is somewhat complicated by the existence of several paradigms for arriving at a ship's general physical arrangement and breakdown into modules for construction. Each involves a different scheme for dealing with questions of spatial arrangement, modularity, affordability, and the use of design budgeting. For example, modularity can be achieved by packaging the mission capabilities into standard containers (for permanent installation) or allocating them to embarked vehicles or containers that can be moved from ship to ship.

Backbone Control Structures. This activity provides for integration of all on-board control resources, in effect making the ship a real "system of systems." Ships are composed of many individual systems. The systems are diverse in organization and purpose but must communicate to permit coordinated action across the entire ship. The control structure must include mechanisms to facilitate cooperation among the divergent elements and parent systems, without compromising their ability to perform their designated tasks. Just as domain models permit a common understanding of goals and requirements at the level of individual systems, the backbones permit a shared understanding of how control functions and interfaces will be handled. Their creation will establish a standard for services available to individual systems and provide guidelines for the design of control structures and interfaces by individual projects. Standards and guidelines created in this manner can be embedded in a development support environment for use at the project level. Creation of standard services will offer potential for dealing with such problems as configuration flexibility, safety certification, fault tolerance, and other key system management issues on a domainwide basis.

Operating Processes. In developing and evaluating ship concepts, boundary conditions for cost, performance, and risk versus capability and affordability drivers must be identified, evaluated, and compared as a system package. This calls for a total ship perspective, together with a capability for detailed analysis of ship characteristics and performance. The basic purpose of this activity is to understand what mission teams must do and how well the ship, as a system of systems, can create and coordinate action paths adequate to meet their needs. This is possible only if experienced operators can be directly involved in efforts to define (and continually improve) primary warfighting processes. This calls for a variety of system engineering assessments, but the main focus should be on process engineering.

The role envisioned for the process assessment activity demands a total ship perspective and capabilities for detailed analysis of ship characteristics and performance. The idea is not to displace the analysis done by individual programs but to integrate available information for assessment of major ship characteristics at the total ship and force levels of consideration. The potential for multipurpose use of sensors and weapons makes it likely that new warfighting capabilities will be identified in such efforts. Each design alternative must be examined from several points of view, including operational effectiveness, functional and physical requirements, potential for upgrade, manning requirements, readiness for transition of key technologies and systems, external interface requirements and capabilities, ability to support and control embarked vehicles, and logistics support capabilities. Suitable MoEs or MoPs (measures of effectiveness or performance) must be identified for conducting systems analysis and tradeoff studies in a total ship context. Specification trees may be used to relate concept designs to (a) performance requirements derived from top-down mission analysis, (b) total ship analysis and engineering efforts, and (c) formulation of acquisition strategies.

Coordination

Layer 2 services provide for coordination of development activities across the many individual projects which contribute to a shipbuilding program. Various techniques can be used to promote system engineering communication across project lines, as shown by Figure 21. The most powerful are (a) use of common reference models and engineering environments; (b) engineering demonstrations and experiments; and (c) an agreed-upon Type A specification. Common access to broad design concepts, and shared information on integration opportunities, may also prove beneficial.

Reference models can help to establish a common language and perspective across the community. Engineering experiments are crucial because they receive wide attention within the technical community. A ship-level Type A specification is a potential vehicle for reaching agreement on a common development framework with all those programs supplying individual systems for ship installation. Terms of reference for any such agreement should include guidelines for consultation in areas of mutual interest and ground rules for coordinating action on matters of common interest to all parties. Coordinated action could mean the use of shared information or plans (concurrent measures) or technical efforts (joint measures) defined to accomplish specific aims. While several ideas are offered here, the executing program office must ultimately determine coordination measures employed and how to implement them.

COOPERATION LEVEL	INSTRUMENTS
Goal Coordination	• Engineering Principles • Integration Architectures
Message-Passing	• Conferences & Publications • Best Practices Exchanges • Standards Evaluation Data
Shared Information Structures	• System of Common Standards • Integrated Database Systems • Engineering Networks
Shared Resources	• Joint Projects / Experiments • System Integration Technology • Compliance Evaluation Teams

FIGURE 21. INSTRUMENTS OF WORK COORDINATION

The recent formation of two new NAVSEA directorates will create new opportunities for coordination across ship acquisition programs. The Directorate for Surface Combatants will be responsible for cruisers, destroyers, frigates, naval guns, and naval surface fire support. The Directorate for Carriers, Littoral Warfare, and Auxiliaries will be responsible for carrier, amphibious assault, auxiliary, and sealift ship types. (It will also handle the remaining nuclear cruisers.) The Directorate for Theater Air Defense also takes on broader responsibilities.

Individual Systems

Layer 3 services define the system engineering processes used for individual systems. In principle, a project is little more than a set of tools, a group of people, and some guidelines by which they work together. However, many different approaches can be used effectively, and it is generally better for each project to use an approach tailored to its needs than to enforce a "one size fits all" approach. Assessing cost and capability from a total ship perspective then becomes difficult. Recently some companies have overcome similar problems using best practices standards identified via benchmarking. There is also considerable potential for improvement at this layer through use of networking, simulation-based design, and physics-based modeling and simulation tools. The target architecture offers a medium by which decisions about ship design and integration strategies can be made and used to define a standard set of services available to the individual systems, along with guidelines for their use by individual projects. The results can be used to create a development environment to support engineering at the individual system level. This can be viewed as a "design backplane," allowing individual projects to adopt a toolkit approach, in which unique services are created and integrated with standard services to form complete designs for application software, equipment, and interfaces. It is envisioned that computer-aided engineering, design, and manufacturing support (CAE/CAD/CAM) tools will be used extensively for this purpose. Engineering aids can be used for analysis, synthesis, and simulation, creating a powerful off-line system for exploratory development of innovative design solutions. At the same time, the backplane will incorporate guidelines to assist individual projects in achieving a common look and feel across the domain. The potential for continuous introduction of new features (through modular computer programs) also exists. As time permits, products with significant reuse potential can be folded into the package of standard services made available by the development support environment.

Individual Products

Layer 4 services are used to describe specific work products of all kinds, essential as components of individual systems. The services involved are governed by specifications that describe technical drawings, documentation, and other data required for product design and production, including geometric and nongeometric data such as form features, tolerances, material properties, and surfaces. In any actual shipbuilding program, the list of products will be lengthy. The services involved are defined by individual project teams in accordance with higher layers of the process model and consist of specific descriptions. Services (procedures, standards, and tools) available from higher layers need not be duplicated at this level.

The standards adopted for the CALS (Computer-Aided Acquisition and Life Cycle Support) project are especially relevant in this area. CALS is a DoD approach that is being adopted worldwide by industry and a large number of nations. The strategy is intended to create a highly integrated and nearly paperless process for engineering, manufacturing, and product support through the computer-aided exchange of information in digital form. Various commercial standards are used toether with MIL-STD-1840 (Automated Interchange of Technical Information), the base standard that provides the overall rules for organizing files of digital data into a CALS-compliant product. MIL-STD-1388-2 is also used to define the relational database management technology for CALS. It is application specific to Logistic Support Analysis Records.

IGES (Initial Graphics Exchange Specification, ANSI / ASME Y14.26M, 1989) and STEP (Standard for Exchange of Product Data, ISO CD 10303) are both applicable standards cited by the DoD Technical Reference Model. IGES permits the exchange of technical two- and three-dimensional drawings, documentation, and other data required for products design and manufacturing, including geometric and nongeometric data such as form features, tolerances, material properties, and surfaces. The information typically associated with CAD/CAM can be described: drawings, wireframe models, surfaces and solids. IGES has some limited product modeling capabilities but its primary purpose is to convey graphics and geometric information. STEP is capable of completely representing product data over its entire life cycle. This representation is suitable for file exchange, as well as for implementing and sharing databases of archived information.

Commercial standards for electronic data interchange (EDI) may also be appropriate at this layer. EDI services are used to create an electronic environment for conducting commerce and achieving significant gains in responsiveness, quality, and savings afforded by such a paperless environment. Examples of applications include vendor search and selection, contract award, product data, payment information, and inventory control. ANSI X.12 and EDIFACT (ISO 9735:1988) are competing standards in this area.

This outline of Layer 4 services (individual products) is the last step in describing a reference model for total ship system engineering. The primary factor in model definition is value delivered to mission teams. The reference framework consists of a set of layered services, with each layer responsible for a defined set of system engineering services. The framework is flexible and reusable, as individual services can be added, modified, or deleted from each layer. A team leader activity is assumed to control the overall design process, including weight, space, and cost budgets; the strategy for integration and control of mission capabilities; and creation of the mission-critical systems which are the reason for taking the ship to sea. Beyond this, it appears that the entire chain of supply should be reinvented to incorporate the best practices of major enterprises around the world.

Potential obstacles to implementation of such a process are considered below. It should be noted that process is only one among several factors that drive enterprise performance. Other important factors are the organizational structure used to carry out the process; the system of management, including incentive structures; and the unifying sense of purpose and direction that knits the people involved into an effective team. Success also depends on the kind of leadership that enables us to cope with change and create the kind of enterprise that can succeed.

TOWARD IMPLEMENTATION

This report begins with a review of total ship engineering concepts. The basics of “system of systems” engineering are given in Chapter 2. Elements of a domain reference model for surface combatants are considered in Chapter 3. An attempt is made in Chapter 4 to reinvent surface ship control structure, and the current chapter considers a matching development process. Overall, four main points can be identified.

- **The development organization must be tailored to the desired architecture and engineering process.**

The first consideration in total ship system engineering is to eliminate stovepiping. In the existing process we develop many independent combat and ship systems and supply them as GFE to builders. Since these component systems are usually developed well in advance of ship building, physical integration is about all that can be achieved, and the ship design team is responsible for most of the key technical decisions. Creating a totally integrated ship, a "system of systems," calls for an integration strategy that extends to control structures and operating processes as well, and can occur today only with major redesign of the component systems.

In this area, implementation depends on two essential tasks. One is to begin forming common backbones applicable to all ship classes. The "herringbone" strategy demonstrated by the Joint Maritime Command Information Systems (JMCIS) can be used to migrate from today's many component programs to a single family of plant control, combat control, and information management backbones. The second key task is to work with element developers (e.g., radars, launchers, generators, machinery) to ensure modularity in design. A total ship version of the Affordability Thru Commonality program should be sought, placing added emphasis on modularity in ordnance and computing elements. For amphibious ship types, cooperation with Marine Corps programs will be needed. Forming integrated product and process development teams can give a starting point.

These changes are necessary to implement a total ship engineering approach, but they must be accompanied by creation of an organization that can work with OPNAV and the Fleet Commanders in Chief (CINCs), the Marine Corps, and the other services to translate joint mission needs and requirements into total ship concepts and designs. The first need is a group to “engineer the force”-- that is, to address how ships will be employed together with other joint operating forces to accomplish broad mission tasks. In part, this involves identification of core mission teams and tasks for future ships and description of core operating processes. This calls for extensive interaction with warfighters. Modeling, assessment, and simulation-based design are key activities.

The role of this group should be matched to that of N8 within OPNAV. Its primary task must be to establish a total ship system engineering process that is based on a clear understanding of Navy mission tasks, and leads to a total Fleet design that reflects a practical strategy for creating and sustaining key mission capabilities. The intent is to attack the root cause of stovepiping, believed to be the absence of a unifying sense of purpose and direction among peers across programs and functional specialties. Change begins at the top.

- **A unifying sense of purpose and direction must be created to knit the people involved into an effective team.**

Overall, the problem is perhaps 80 percent organizational and cultural, and only about 20 percent technical. The kind of leadership that enables people to cope with change and create a virtual enterprise from a large array of participating activities is crucial to success. This means the following:

- o Direction: Setting a direction means creating vision and strategies, rather than plans and budgets. The aim is to describe the enterprise in terms of what it should become in the long run, and to devise a feasible way of achieving this goal. (We can agree on plans and budgets but still get in each other's way.)

- o Movement: Getting a group of people to move in the same direction takes more than organization. It means communicating a vision and strategy to anyone who can help or block their achievement.

- o Energy: Just as direction setting identifies an appropriate path for movement, and effective alignment gets people moving down that path, successful motivation generates the energy to overcome obstacles. This depends more on appealing to basic human needs, values, and emotions via informal networks rather than formal planning, organization, and control.

It is difficult to create a foundation for total ship system engineering that spans all the disciplines (technical and operational) involved. The trouble is that each discipline has its own conceptual framework, tailored to the goals, values, and character of its work and fundamental to effective teamwork. This framework is passed to each generation of recruits and colors perception of new ideas, sometimes making them seem irrelevant or contrary to accepted methods or bodies of knowledge. Fortunately, this is an obstacle that can also be a solution; i.e., an appropriate conceptual framework must be established to support total ship system engineering. In essence, this report is aimed at producing such a framework, with associated design concepts, standards, and tools.

- **Backbones are the key to building warships as systems.**

The advantages of a common backbone apply not only to combat control (mission operations), but also to plant control and readiness, and to the area of information management as well. What is envisioned is a generic backbone (with variants for each area) that supports design for modularity, commonality, and the sharing of functional resources on a shipwide basis. The generic backbone would provide the following characteristics:

- o Command spaces become utilities, tailorable to any set of mission teams and tasks which may be operationally required.

- o Computing, communication, and display resources are managed on a shipwide basis, with a common application environment maintained.

- o Readiness assessment and resource control are managed on a shipwide basis.

- o Life cycle costs are reduced through use of common building blocks and open systems on a shipwide basis for all categories of systems, with manning and parts counts held to minimum levels.

Total ship engineering is important because it appears feasible to arrive at an enduring architecture for surface combatants, flexible enough to permit (a) application to a variety of ship types and designs; (b) insertion of new functionality as warfighting systems evolve; and (c) incorporation of new technology as it becomes available. A key aspect of modern technology is the potential for gains in capability and affordability through the sharing of resources across subsystem and element boundaries. Resources which can be shared in this way include sensors, computers and displays; magazines and launchers; ship services such as electrical power; and computer applications. The idea of a family of common backbone systems is promising, although much remains to be done. On the other hand, failure to design surface combatants as systems may produce, in time, a Fleet that can't support what the warfighters must do.

- **Warfighters must be involved in the development process.**

Today, change and uncertainty exist in every part of the process by which naval forces are produced and employed. Flexibility is a major consideration in building forces to cope with an uncertain future. It is expected that flexibility will enable US forces to respond quickly to emerging threats, extend US reach to any part of the globe, and adopt new technologies with ease. Flexibility takes many forms. For example, a ship may be equipped to perform a large number of tasks within a single mission area. Thus an aircraft carrier can launch and recover many sorties per day or only a few, as dictated by operational tempo. Another form of flexibility involves the performance of tasks in multiple mission areas, shifting from one to another as the situation demands. This kind of flexibility allows a deployed force to handle emerging threats without waiting for special purpose units, and is often associated with quick response operations. "Multimission" ships tend to be large and expensive, relative to single-mission ships, as they must carry a variety of sensors and weapons. Large aircraft carriers have this kind of flexibility because they carry a mix of aircraft types.

Normally, even multimission ships have a limited array of capabilities. A given design could perform well in certain scenarios and poorly in others. Thus a third kind of flexibility might call for a ship that can tailor its capabilities to various operating scenarios, each calling for a different mix. Ideally, ships with this kind of flexibility can cope with a severe threat in a particular mission area, or a diverse threat mix that involves several mission areas. Tailored flexibility appears to offer the best hope for coping with the current era of uncertainty.

Having acknowledged the importance of flexibility, many look to computers and automation as the key to improvement. However, the brilliance of the technology tends to obscure the importance of articulating precisely what kind of flexibility is necessary and defining a strategy for achieving it. The bulk of lessons learned from industry efforts to enhance flexibility through computer integration indicates that success depends more on people than any technical factor. We expect experienced teams can handle a wider range of tasks than novice teams, but even very experienced teams can have difficulty adapting to change. In particular, leadership appears to play a key role in identifying the kind of flexibility needed and when it is appropriate. This is fundamental in a practical approach to automation.

What seems most promising, for improved flexibility, is not automation to replace people, but automation that will assist people in tailoring systems and procedures to the changing conditions. More is gained by helping people to make better decisions than by cutting them out of the decision-making process. In short, since we are not likely to know in advance exactly what the warfighters will be called on to do, we must enable them to make appropriate decisions in the field. The warfighter's role must be clearly identified in overall surface ship architectures, and mission teams must be provided with the information needed to carry out that role.

This calls for a special kind of automation. In humans, the autonomic nervous system works without regard to conscious thought processes and allows key control decisions to be made at the lowest possible level. Flexible response is achieved by use of a distributed approach in making decisions about system structure. Real flexibility can be achieved only if these decisions are made by people on the scene, without having to consult the designers who correspond to the brain in the ship engineering process. Future combatants should be designed so the necessary judgments (about mission teams, battle doctrine, information flow paths, etc.) are made by the warfighters. To that end, it is essential to have direct involvement by experienced mission teams in ship design and development. This does not mean less rigor in design engineering; it may mean the job will get a bit tougher.

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